

# RASS-SDSS Galaxy Cluster Survey. V.

## The X-ray-Underluminous Abell Clusters.

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**Abstract.** In this paper we consider a large sample of optically selected clusters, in order to elucidate the physical reasons for the existence of X-ray underluminous clusters. For this purpose we analyze the correlations of the X-ray and optical properties of a sample of 137 spectroscopically confirmed Abell clusters in the SDSS database. We search for the X-ray counterpart of each cluster in the ROSAT All Sky Survey. We find that 40% of our clusters have a marginal X-ray detection or remain undetected in X-rays. These clusters appear too X-ray faint on average for their velocity dispersion determined mass, i.e. they do not follow the scaling relation between X-ray luminosity and virial mass traced by the other clusters. On the other hand, they do follow the general scaling relation between optical luminosity and virial mass. We refer to these clusters as the X-ray-Underluminous Abell clusters (AXU clusters, for short) and designate as 'normal' the X-ray detected Abell systems. We examine the distributions and properties of the galaxy populations of the normal and the AXU clusters, separately. The AXU clusters are characterized by leptokurtic (more centrally concentrated than a Gaussian) velocity distribution of their member galaxies in the outskirts ( $1.5 < r/r_{200} \leq 3.5$ ), as expected for the systems in accretion. In addition, the AXU clusters have a higher fraction of blue galaxies in the external region and show a marginally significant paucity of galaxies at the center. Our results seem to support the interpretation that the AXU clusters are systems in formation undergoing a phase of mass accretion. Their low X-ray luminosity should be due to the still accreting intracluster gas or to an ongoing merging process.

### 1. Introduction

Clusters of galaxies are extremely important astrophysical tools. They are the most massive gravitationally bound systems in the universe. Since they sample the high mass end of the mass function of collapsed systems, they can be used to provide tight constraints on cosmological parameters such as  $\Omega_m$ ,  $\sigma_8$  and  $\Lambda$  (Eke et al. 1996, Donahue & Voit 1999). Moreover they are extremely powerful laboratories to study galaxy formation and evolution. To investigate the global properties of the cosmological background it is necessary to construct and study a large sample of clusters (Borgani & Guzzo 2001).

Several techniques exist to build cluster samples, each based on different clusters properties. The first attempts at a large, homogeneous survey for galaxy clusters was conducted by Abell (1958) with the visual identification of clusters on the Palomar Observatory Sky Survey (POSS) photographic plates. Similar catalogues were constructed by Zwicky and collaborators (Zwicky et al. 1968). Since then, a large number of optically selected samples have been constructed with automated methods: EDCC (Edinburgh Durham Cluster Catalogue; Lumdsen et al. 1992), APM (Automatic Plate measuring; Dalton et al. 1994), PSCS (Palomar Distant Cluster Survey; Postman et al. 1996), EIS (ESO Imaging Cluster

Survey; Olsen et al. 1999), ENACS (ESO Nearby Abell Cluster Survey; Katgert et al. 1996, Mazure et al. 1996), RCS (Red sequence Cluster Survey; Gladders & Yee 2000) and the samples derived from the Sloan Digital Sky Survey (Goto et al. 2002; Bahcall et al. 2003). The advantage of using optical data is that in general it is relatively easy to build large optically selected cluster catalogs, which allow one to investigate cluster properties with a statistically solid data-base. On the other hand, the main disadvantage of the optical selection is that the selection procedure can be seriously affected by projection effects. Only a very observationally expensive spectroscopic campaign can confirm the overdensities in 3 dimensions.

In 1978, the launch of the first X-ray imaging telescope, the *Einstein* observatory, began a new era of cluster discovery, as clusters proved to be luminous ( $\geq 10^{42-45}$  ergs s<sup>-1</sup>), extended ( $r \gtrsim 1$  Mpc) X-ray sources, readily identified in the X-ray sky. Therefore, X-ray observations of galaxy clusters provided an efficient and physically motivated method of identification of these structures. The X-ray selection is more robust against contamination along the line-of-sight than traditional optical methods, because the X-ray emission, unlike galaxy overdensities, is proportional to the square of the (gas) density. The ROSAT satellite with its large field of view and better sensi-

tivity, allowed to a leap forward in the X-ray cluster astronomy, producing large samples of both nearby and distant clusters (Castander et al. 1995; Ebeling et al. 1996a, 1996b; Scharf et al. 1997; Ebeling et al. 2000; Böhringer et al. 2001; Gioia et al. 2001; Böhringer et al. 2002; Rosati et al. 2002 and references therein). The disadvantage of X-ray cluster surveys is their lower efficiency and higher observational cost as compared to optical surveys.

It is clear that understanding the selection effects and the biases due to the different cluster selection techniques is crucial for interpreting the scientific results obtained from such different cluster samples. Castander et al. (1994) used ROSAT to observe cluster candidates in the redshift range 0.7–0.9 from the 3.5 square degree subsample of Gunn et al.’s (1986) optical cluster catalog and found surprisingly weak X-ray emission. Bower et al. (1994) undertook ROSAT X-ray observations of optically selected clusters from Couch et al.’s (1991) 46 deg<sup>2</sup> catalog. Bower et al. (1994) selected a random subset of the full catalogue, in the redshift range 0.15–0.66. The X-ray luminosity of almost all the selected clusters was found to be surprisingly low, suggesting, on the one hand, substantial evolution of the X-ray luminosity function between redshift  $z = 0$  and  $z \sim 0.4$ , and, on the other hand, overestimated velocity dispersions for the nearby X-ray underluminous clusters, perhaps as a consequence of the contamination by galaxy filaments and of radial infall of field galaxies into the clusters. Similar results were obtained by Holden et al. (1997).

With the ROSAT Optical X-ray Survey (ROXS), Donahue et al. (2002) concluded that there is little overlap between the samples of X-ray-selected and optically-selected galaxy clusters. Only  $\sim 20\%$  of the optically selected clusters were found in X-rays, while  $\sim 60\%$  of the X-ray clusters were also identified in the optical sample. Furthermore, not all of the X-ray detected clusters had a prominent red-sequence, something that could introduce a selection bias in those cluster surveys based on colour information (Goto et al. 2002, Gladders & Yee 2000). Ledlow et al. (2003) analyzed the X-ray properties of a sample of nearby bright Abell clusters, using the ROSAT All-Sky Survey (RASS). They found an X-ray detection rate of 83%. Gilbank et al. (2004) explored the biases due to optical and X-ray cluster selection techniques in the X-ray Dark Cluster Survey (XDCS). They found that a considerable fraction of the optically selected clusters do not have a clear X-ray counterpart, yet spectroscopic follow-up of a subsample of X-ray underluminous systems confirmed their physical reality. Lubin et al. (2004) analyzed the X-ray properties of two optically selected clusters at  $z \geq 0.7$ , with XMM-Newton. They found the two clusters are characterized by X-ray luminosities and temperatures that are too small for their measured velocity dispersion. Similar results were obtained in the XMM-2dF Survey of Basilakos et al. (2004). They found many more optical cluster candidates than X-ray ones. Deeper XMM data confirmed that their X-ray undetected cluster candidates have intrinsically very low X-ray luminosities.

In this paper we consider a large sample of optically- and X-ray-selected clusters, in order to elucidate the physical reasons for the existence of underluminous optical/X-ray clusters. The starting point of this work is the analysis we con-

ducted on a sample of X-ray selected clusters sample (Popesso et al. 2005a, Paper III of this series). 90% of those systems are taken from the REFLEX and NORAS catalogs, which are X-ray flux-limited cluster catalogs entirely built upon the ROSAT-All-Sky Survey (RASS). The remaining 10% of that sample are groups or faint clusters with X-ray fluxes below the flux limits of REFLEX and NORAS. In Paper III we found an optical counterpart for each of the X-ray selected clusters of the RASS. Using Sloan Digital Sky Survey (SDSS, see, e.g., Abazajian et al. 2003) optical data for these clusters, we then studied the scatter of the correlations between several optical and X-ray cluster properties (X-ray and optical luminosities, mass, velocity dispersion and temperature). In this paper we extend our analysis to a sample of *optically* selected clusters.

The paper is organized as follows. In section 2 we describe the data and the sample of optically selected clusters used for the analysis. We also describe how we measure the optical luminosity, the velocity dispersion, the mass and the X-ray luminosity of the clusters. In section 3 we analyze the correlation of both the X-ray and the optical cluster luminosities with their masses. In section 4 we describe the optical properties of the Abell clusters without clear X-ray detection and compare them with those of normal X-ray emitting Abell systems. In section 6 we discuss our results and give our conclusions.

We adopt a Hubble constant  $H_0 = 70 \text{ h km s}^{-1} \text{ Mpc}^{-1}$ , and a flat geometry of the Universe, with  $\Omega_m = 0.3$  and  $\Omega_\Lambda = 0.7$  throughout this paper.

## 2. The data

The optical data used in this paper are taken from the SDSS (Fukugita et al. 1996, Gunn et al. 1998, Lupton et al. 1999, York et al. 2000, Hogg et al. 2001, Eisenstein et al. 2001, Smith et al. 2002, Strauss et al. 2002, Stoughton et al. 2002, Blanton et al. 2003 and Abazajian et al. 2003). The SDSS consists of an imaging survey of  $\pi$  steradians of the northern sky in the five passbands  $u, g, r, i, z$ , covering the entire optical range. The imaging survey is taken in drift-scan mode. The imaging data are processed with a photometric pipeline specially written for the SDSS data (PHOTO, Lupton et al. 2001). For each cluster we defined a photometric galaxy catalog as described in Section 3 of Popesso et al. (2004, Paper I of this series, see also Yasuda et al. 2001). For the analysis in this paper we use only SDSS Model magnitudes.

The spectroscopic component of the survey is carried out using two fiber-fed double spectrographs, covering the wavelength range 3800–9200 Å, over 4098 pixels. They have a resolution  $\Delta\lambda/\lambda$  varying between 1850 and 2200, and together they are fed by 640 fibers, each with an entrance diameter of 3 arc-sec.

The X-ray data are taken from the RASS. The RASS was conducted mainly during the first half year of the ROSAT mission in 1990 and 1991 (Trümper 1988). The ROSAT mirror system and the Position Sensitive Proportional counter (PSPC) operating in the soft X-ray regime (0.1–2.4 keV) provided optimal conditions for the studies of celestial objects with low surface brightness. In particular, due to the unlimited field of view of the RASS and the low background of the PSPC. This

dataset is ideal to investigate the properties of nearby clusters of galaxies.

## 2.1. The cluster samples

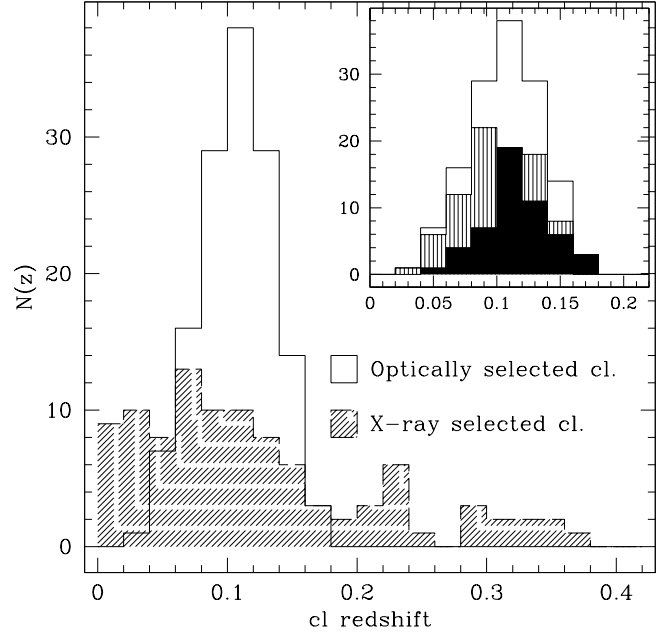
### 2.1.1. The X-ray selected cluster sample

As reference X-ray cluster sample for the comparison between X-ray and optically selected clusters, we consider a subsample of the X-ray selected RASS-SDSS Galaxy Cluster Sample of Popesso et al. (2005b). The RASS-SDSS galaxy cluster catalog comprises 130 systems detected in the ROSAT All Sky Survey (RASS). The X-ray cluster properties and the redshifts have been taken from different catalogs of X-ray selected clusters: the ROSAT-ESO flux limited X-ray cluster sample (REFLEX, Böhringer et al. 2001, 2002), the Northern ROSAT All-sky cluster sample (NORAS, Böhringer et al. 2000), the NORAS 2 cluster sample (Retzlaff 2001), the ASCA Cluster Catalog (ACC) from Horner et al. (2001) and the Group Sample (GS) of Mulchaey et al. (2003). The subsample considered in this paper comprises the RASS-SDSS galaxy clusters with known mass (either the virial estimate from optical data, or, when this is not available, the mass derived from the X-ray temperature) for a total number of 102 systems (69 cluster with known optical mass + 33 clusters with mass derived from the mass-temperature relation). The sample is drawn from the SDSS DR2 imaging data which cover 3324 square degrees. The considered cluster sample covers the entire range of masses and X-ray/optical luminosities, from very low-mass and X-ray/optical faint groups ( $10^{13} M_{\odot}$ ) to very massive and X-ray/optical bright clusters ( $5 \times 10^{15} M_{\odot}$ ). The cluster sample comprises mainly nearby systems at the mean redshift of 0.1 and few objects (10) in the range  $0.25 \leq z \leq 0.37$ . The redshift distribution of the cluster sample is shown in Fig. 1.

### 2.1.2. The optically selected cluster sample

The optically selected cluster sample considered in this paper is a subsample of the Abell cluster catalog (Abell 1958). We have selected all the Abell clusters in the region covered by the 3<sup>rd</sup> data release (DR3) of the SDSS (5282 deg<sup>-2</sup>). The Abell catalog is based on a visual inspection of galaxy overdensities. Therefore, it is affected by the presence of spurious detections due to projection effects. To exclude the spurious clusters from the catalog, we consider only the clusters with a spectroscopic confirmation of the galaxy overdensity. For this, we use the SDSS spectroscopic catalog, which provides spectra and redshifts for more than 250,000 galaxies with Petrosian magnitude  $r_{\text{Petro}} \leq 17.77$ .

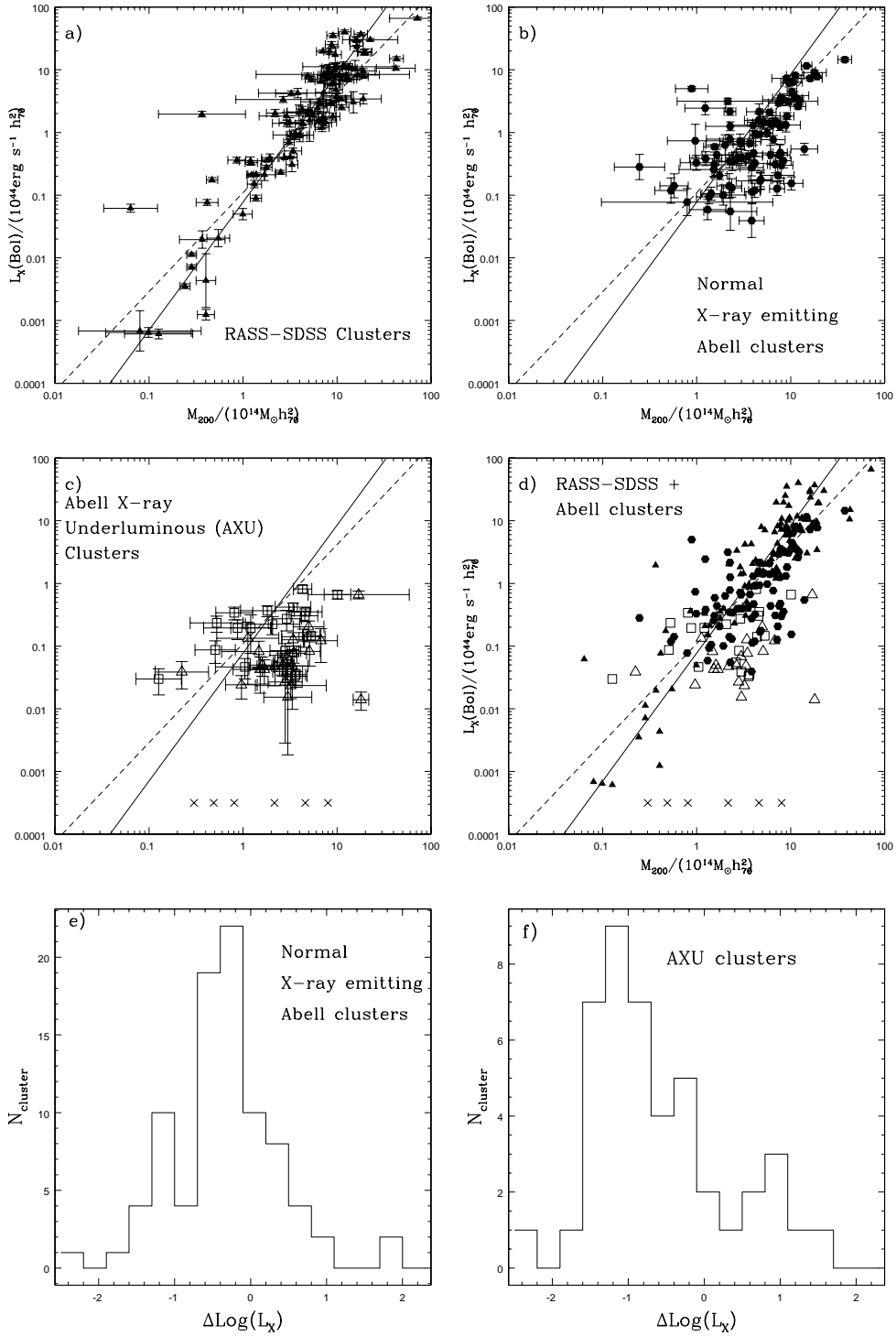
We estimate the mean cluster spectroscopic redshift  $z_c$  as the peak of the overdensity in the redshift distribution of the galaxies around the cluster coordinates. Since the purpose of this paper is to compare optical and X-ray properties of galaxy clusters, it is extremely important to avoid misclassification between the optical and the X-ray sources. Therefore, we have checked our estimations of the mean cluster redshift with those available in the literature, as well as with the photometric  $z_c$  estimate obtained from the relation that links the mean redshift



**Fig. 1.** Redshift distribution of the X-ray and optically selected, respectively, cluster samples used in this paper. The solid line in the main panel shows the redshift distribution of the optically selected cluster sample and the shaded histogram is the redshift distribution of the X-ray clusters. The small panel in the figure shows the redshift distribution of the X-ray detected (grey histogram) and the X-ray undetected (black histogram) optically selected clusters. The solid line in the small panel shows the redshift distribution of the whole optically selected cluster sample for comparison.

of a cluster with the apparent magnitude of its tenth brightest galaxy (Abell et al. 1989). Clusters for which discrepancies were found among the different  $z_c$  estimates are excluded from the final sample used in this paper.

Cluster members are selected among SDSS galaxies with available redshifts, as follows. First, we select only galaxies within a circle of 2.15 Mpc radius (the Abell radius). We then group together those galaxies with intergalaxy velocity differences less than a critical value that depends on the total number of galaxies along the line-of-sight, according to the relation adopted by Adami et al. (1998a). This allows us to define the cluster limits in velocity space. As an additional step, we apply the membership selection algorithm of Katgert et al. (2004) to all the galaxies (also outside an Abell radius) with velocities within the limits defined with the gapper procedure. This algorithm takes into account both the velocities and the cluster-centric positions of the galaxies. The method is identical to that of den Hartog & Katgert (1996) when the cluster sample contains at least 45 galaxies, and it is a simplified version of it for smaller samples (for more details, see Appendix A in Katgert et al. 2004). It requires a cluster centre to be defined. When possible, we adopt the X-ray centre for this. However some clusters do not have secure X-ray detection, in which case the



**Fig. 2.**  $L_X - M_{200}$  relation. Panel a) shows the  $L_X - M_{200}$  of the X-ray selected RASS-SDSS cluster sample (filled triangles). Panel b) shows the location of the Normal X-ray emitting Abell clusters (filled dots) relatively to the best fit obtained in the X-ray selected sample. Panel c) shows the location of the AXU systems in the same diagram. The empty squares are the Abell clusters with marginally significant X-ray emission and the empty triangles are the Abell clusters without X-ray emission (upper limits, see text for the explanation), the crosses are the Abell clusters for which the GCA method was not able to calculate the  $L_X$  upper limit (they are all plotted at  $L_X = 10^{-40.5} \text{ erg s}^{-1}$ ). Panel d) shows the  $L_X - M_{200}$  relation for the RASS-SDSS plus the whole Abell sample. The symbols in the panel have the same meaning as in the previous three panels. The solid line in the 4 panels is the best fit line obtained in the whole X-ray selected sample of panel a) and the dashed line is the best fit obtained from the subsample of 69 RASS-SDSS clusters for which the mass is calculated as for the Abell clusters. Panel e) shows the distribution of the residuals of the normal X-ray emitting clusters. Panel f) shows the same distribution for the AXU clusters. The residuals are defined as  $\Delta \log(L_X) = \log(L_{X,m}) - \log(L_{X,p})$ , where  $L_{X,m}$  is the measured cluster X-ray luminosity and  $L_{X,p}$  is the  $L_X$  predicted by the  $L_X - M_{200}$  X-ray relation.

X-ray centre cannot be accurately defined. In those cases we take the position of the brightest cluster member as the cluster centre (see, e.g., Biviano et al. 1997). In any case, the analysis of clusters identified in cosmological numerical simulations indicate that the choice of the centre is not critical for a correct performance of the membership selection algorithm (Biviano et al. in preparation).

Only Abell clusters with at least 10 galaxy members are selected, since 10 is the minimum number of cluster members in order to calculate in a reasonable way the cluster mass and velocity dispersion (Girardi et al. 1993). Among the 280 Abell clusters in the region covered by DR3, 179 fulfil this requirement. Among these clusters, 38 are affected by problems of contamination, due to the presence of a close companion or a second system along the same line-of-sight but at different redshift and 4 show large discrepancies between our estimate of  $z_c$  and the value derived from the literature or the  $z_c - m_{10}$  relation (Postman 1985). Those systems are excluded from our final sample. Hence we are left with a sample of 138 Abell clusters, listed in the Appendix, along with their global properties. As shown in Fig. 1, the considered cluster sample comprises only nearby systems ( $z < 0.25$ ) at the mean redshift of 0.1. As the X-ray reference sample, the optically selected cluster sample covers the entire range of masses and X-ray/optical luminosities, from the low-mass (faint X-ray/optical luminosity) regime ( $2 \times 10^{13} M_\odot$ ) to the high-mass (high X-ray/optical luminosity) regime ( $3 \times 10^{15} M_\odot$ ). We point out that the two cluster samples (X-ray and optically selected) considered in this work are not complete. However, for the purpose of this work we do not need complete cluster samples but clean X-ray and optically selected cluster samples spanning the all cluster mass and luminosity range. The X-ray and optically selected cluster samples used in this work fulfill these requirements.

## 2.2. Optical luminosities

The estimate of the optical luminosity of a cluster,  $L_{op}$ , requires subtraction of the foreground and background galaxy contamination. We consider two different approaches to the statistical subtraction of the galaxy background. We compute the local background number counts in an annulus around the cluster and a global background number counts from the mean of the magnitude number counts determined in five different SDSS sky regions, each with an area of  $30 \text{ deg}^2$ . In our analysis we show the results obtained using the optical luminosity estimated with the second method, since the two methods produces only marginal differences in the  $L_{op}$  estimates. The cluster magnitude number counts in the virial region are obtained by subtracting from the galaxy counts measured within  $r_{200}$  the local (global) field counts rescaled to the cluster area. The cluster magnitude number counts are converted in luminosity number counts after dereddening, K-correcting and transforming in absolute magnitudes the apparent magnitudes. The cluster Optical Luminosity is then obtained simply by summing up the luminosity number counts multiplied by the mean luminosity of the bin. The reader is referred to paper I of this series for the details about the comparison between optical luminosities ob-

tained with different background subtraction methods and for the other technical details.

## 2.3. Velocity dispersions and virial masses

The virial analysis (see, e.g., Girardi et al. 1998) is performed on the clusters with at least 10 member galaxies. The velocity dispersion is computed on the cluster members, using the biweight estimator (Beers et al. 1990). The virial masses are corrected for the surface pressure term (The & White 1986) by adopting a profile of Navarro et al. (1996, 1997; NFW hereafter) with a concentration parameter,  $c$ , that depends on the initial estimate of the cluster virial mass itself. The  $c$ -mass relation is given by  $c = 4 \times (M/M_{KBM})^{-0.102}$  where the slope of the relation is taken from Dolag et al. (2004), and the normalization  $M_{KBM} \simeq 2 \times 10^{15} M_\odot$  from Katgert et al. (2004). The clusters in our sample span a range  $c \simeq 3-6$ .

Correction for the surface pressure term requires knowledge of the  $r_{200}$  radius, for which we adopt Carlberg et al.'s (1997) definition (see eq.(8) in that paper) as a first guess. After the virial mass is corrected for the surface pressure term, we refine our  $r_{200}$  estimate using the virial mass density itself. Say  $M_{vir}$  the virial mass (corrected for the surface term) contained in a volume of radius equal to a chosen observational aperture,  $r_{ap}$ , that we have set equal to the Abell radius, 2.15 Mpc. The radius  $r_{200}$  is then given by:

$$r_{200} \equiv r_{ap} [\rho_{vir}/(200\rho_c)]^{1/2.4} \quad (1)$$

where  $\rho_{vir} \equiv 3M_{vir}/(4\pi r_{ap}^3)$  and  $\rho_c(z)$  is the critical density at redshift  $z$  in the adopted cosmology. The exponent in eq.(1) is the one that describes the average cluster mass density profile near  $r_{200}$ , as estimated by Katgert et al. (2004) for an ensemble of 59 rich clusters.

For consistency the  $c$ -mass relation is used to interpolate (or, in a few cases, extrapolate) the virial mass  $M_{vir}$  from  $r_{ap}$  to  $r_{200}$ , yielding  $M_{200}$ . From  $M_{200}$  the final estimate of  $r_{200}$  is obtained, using the definition of  $M_{200}$  itself.

Even if the completeness level of the SDSS spectroscopic sample is very high, in the central regions of galaxy clusters such a level is likely to drop because fibers cannot be placed closer than 55 arcsec. We estimate that the spectroscopic completeness drops to  $\sim 70\%$  in the central  $\sim 0.1$  Mpc cluster regions. This affects the observed number density profile of a cluster, and hence our virial mass estimates (see, e.g., Beers et al. 1984). Using the average cluster number density profile we estimate that this effect of incompleteness translates into an average over-estimate of the virial mass of only  $\sim 5\%$  (see Paper III of the series for more details about this estimate). Since the effect is very small, and much smaller than the observational uncertainties, we neglect this correcting factor in the following analysis.

## 2.4. X-ray luminosities

In order to create a homogeneous catalog of X-ray cluster properties, we search for the X-ray counterparts of all the 137 Abell clusters, and compute their X-ray luminosity,  $L_X$ , using only RASS data.

X-ray luminosities are calculated with the growth curve analysis (GCA) method used for the NORAS and REFLEX cluster surveys (Böhringer et al. 2000) based on the RASS3 data base (Voges et al. 1999). The GCA method is optimized for the detection of the extended emission of clusters by assessing the plateau of the background subtracted cumulative count rate curve. We use as a final result the total flux inside the radius  $r_{200}$  which is corrected for the missing flux estimated via the assumption of a standard  $\beta$ -model for the X-ray surface brightness (see Böhringer et al. 2000 for more details). The correction is typically only 8 – 10% illustrating the high effectiveness of the GCA method to sample the flux of extended sources.

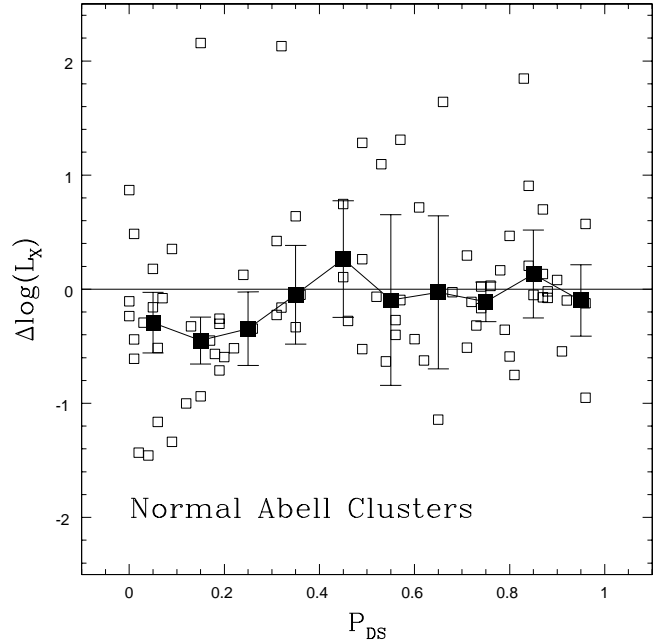
We check by eye all the X-ray sources associated to the Abell clusters. We find a secure X-ray detection for 86 systems out of the 137 isolated and well classified Abell clusters. Other 27 have a marginally significant detection (between 2 and 3  $\sigma$ ) and other 24 do not have clear X-ray emission (detection level  $\sim 1\sigma$  or no detection at all). The GCA method provides an estimate of the X-ray detection also in case of dubious X-ray detection, but the percentage error is higher than 80% and the estimate has to be considered as an upper limit. In 7 cases out of the 24 systems without X-ray detection the GCA method fails completely to provide an estimate of  $L_X$ . The X-ray luminosity ended up to be negative after the background subtraction. For those systems the X-ray luminosity is set equal to zero. We will discuss in detail the nature of these 27+24 clusters with marginal or no X-ray detection in the following sections. We refer to these 51 systems in the next paragraph as “clusters without secure X-ray detection”.

### 3. X-ray versus optical properties

In this section we analyze the relations among the Bolometric X-ray luminosity, the cluster mass,  $M_{200}$ , and the optical  $i$ -band luminosity,  $L_{op}$ . The Bolometric X-ray luminosity is derived by correcting the X-ray luminosity in the ROSAT energy band (0.1-2.4 keV) with the bolometric correction corresponding to the cluster temperature. The cluster temperature is estimated from the cluster mass using the  $T_X - M_{200}$  relation given in Paper III. We perform an orthogonal linear regression in logarithmic space for each of the analyzed relations. The orthogonal regression is performed with the software package ODRPACK (Akritas & Bershady 1996). Table 1 lists the values of the best fit parameters and the scatter for all the analysed correlations.

#### 3.1. The $M - L_X$ relation and the Abell X-ray Underluminous Clusters

Panel *a*) of Fig. 2 shows the  $L_X - M_{200}$  relation obtained from the X-ray selected RASS-SDSS galaxy cluster sample. The RASS-SDSS galaxy cluster sample comprises 102 systems. For 69 of them the mass,  $M_{200}$ , is calculated through the dynamical analysis as explained in section 2.3. For the remaining 33 objects the mass is calculated using the known ICM temperature in the M-T relation given in paper III. The solid line in the panel *a*) of Fig. 2 shows the best fit line obtained with the whole sample (102 clusters) and the dashed line shows the best fit line ob-



**Fig. 3.** The X-ray luminosity residuals  $\Delta\log(L_X)$  from the best-fit  $L_X - M_{200}$  relation of normal Abell clusters, vs. the Dressler & Shectman parameter  $P_{DS}$ . Systems with  $P_{DS} < 0.1$  are considered to be characterized by subclustering. Filled squares with error bars represent the mean and dispersion of all points in bins of  $P_{DS}$ .

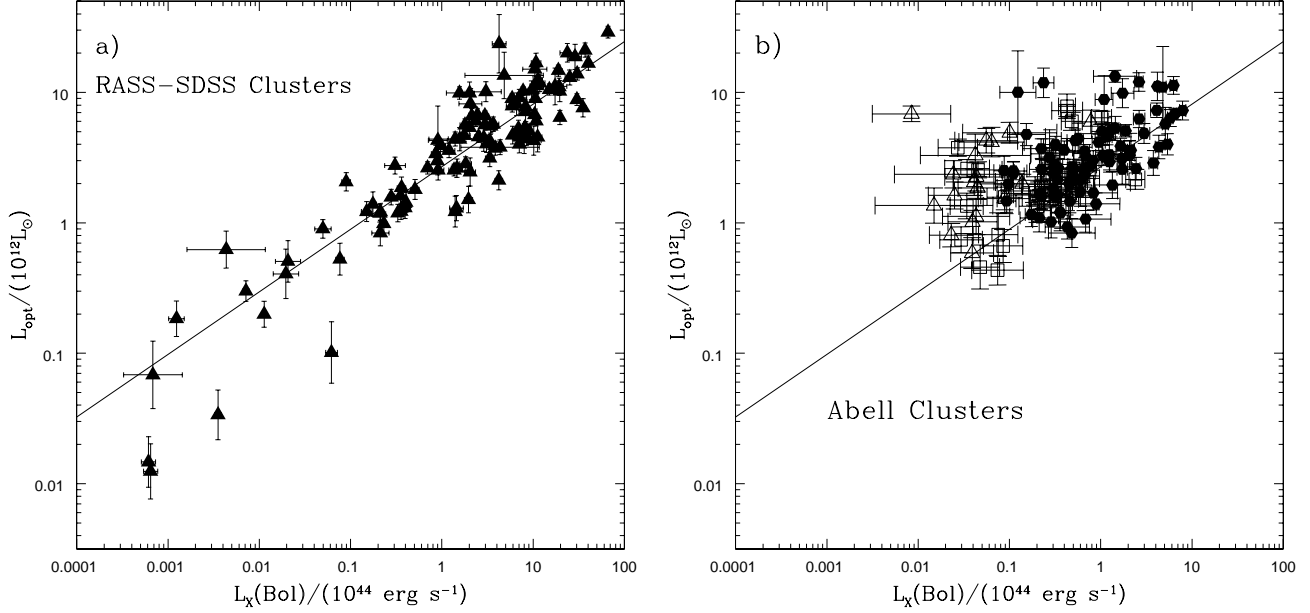
tained using the 69 clusters for which the mass is calculated as for the Abell Clusters.

Panel *b*) of Fig. 2 shows the location of the 86 Abell clusters with clear X-ray detection in RASS relatively to the best fit obtained on the X-ray selected sample. Panel *c*) shows the behaviour of the Abell systems without secure X-ray detection in RASS in the same diagram.

As shown by panel *d*) of Fig. 2, the scatter of the  $L_X - M_{200}$  relation increases significantly when the Abell clusters are added to the sample of RASS-SDSS clusters. The best fit parameters of the  $L_X - M_{200}$  relation obtained by considering the Abell and RASS-SDSS clusters together is consistent with the relation found for the RASS-SDSS clusters only (see Table 1). However, the orthogonal scatter increases from 44 to 65%. The RASS-SDSS clusters sample comprises several cluster (10 objects) at redshift higher than the redshift range of the Abell clusters. Thus, to check the possible effect of evolution on the scatter of the considered relation, we perform the analysis considering the RASS-SDSS clusters in the same redshift range as the Abell clusters. The resulting correlations are perfectly consistent with the results listed in Table 1 for all the considered cluster sample. The scatter increase is not only due to the Abell clusters without clear X-ray detection. Instead, a large contribution to the increase of the scatter is given by the normal Abell clusters which show a high level of subclustering. In fact, the presence of substructures causes the cluster mass to be overestimated. Therefore the systems presenting subclustering

A-B relation		sample					
A	B		$\alpha$	$\beta$	$\sigma$	$\sigma_B$	$\sigma_A$
$L_X(Bol)$	$M_{200}$	X-ray	$2.04 \pm 0.08$	$-1.11 \pm 0.06$	0.16	0.21	0.43
		Abell	$2.19 \pm 0.14$	$-1.67 \pm 0.14$	0.23	0.32	0.48
		A+X-ray	$2.12 \pm 0.08$	$-1.32 \pm 0.07$	0.22	0.29	0.48
		$A(P_{DS} > 0.1) + X - ray$	$2.06 \pm 0.08$	$-1.21 \pm 0.06$	0.18	0.23	0.46
$L_X(Bol)$	$L_{op}$	X-ray	$1.72 \pm 0.08$	$-0.98 \pm 0.07$	0.17	0.19	0.31
		Abell	$2.01 \pm 0.15$	$-1.17 \pm 0.09$	0.20	0.28	0.35
		A+X-ray	$1.87 \pm 0.08$	$-1.08 \pm 0.06$	0.19	0.25	0.35
$L_{op}$	$M_{200}$	X-ray	$0.88 \pm 0.03$	$-0.08 \pm 0.02$	0.13	0.18	0.16
		Abell	$0.80 \pm 0.07$	$-0.01 \pm 0.04$	0.14	0.21	0.22
		A+X-ray	$0.83 \pm 0.03$	$-0.05 \pm 0.03$	0.14	0.20	0.19

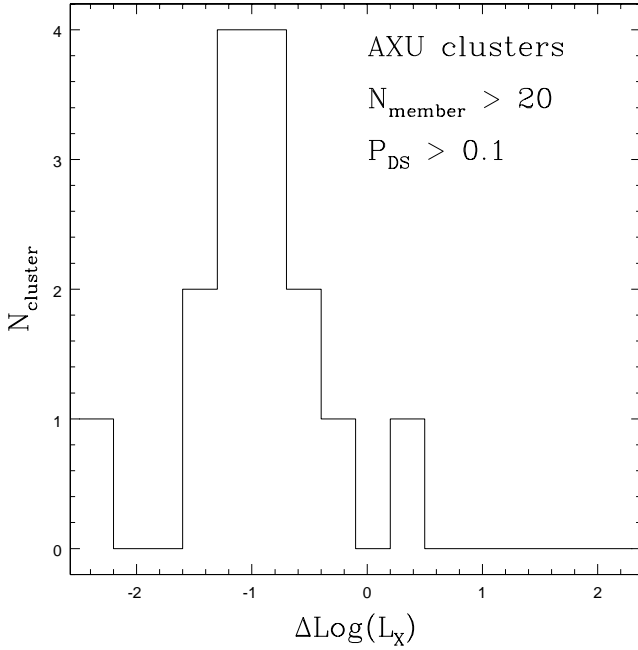
**Table 1.** The table lists the best fit parameters for the relations between several global cluster quantities, i.e. the bolometric X-ray luminosity,  $L_X(Bol)$ , the virial mass,  $M_{200}$ , and the  $i$ -band optical luminosity  $L_{op}$ , for different samples of galaxy clusters. The 'X-ray' refers to the X-ray selected systems with known mass, taken from the RASS-SDSS galaxy cluster catalog (Paper III). The 'Abell' refers to the whole Abell sample considered in this work. The 'A+X-ray' refers to the Abell sample plus the X-ray selected cluster sample. The ' $A(P_{DS} > 0.1) + X - ray$ ' refers to the X-ray selected clusters plus the Abell sample without the clusters with unsecure X-ray detection and the systems with high level of subclustering. The table lists three estimations of the scatter for each relation:  $\sigma$  is the orthogonal scatter of the A-B relation (where  $A = 10^\beta \times B^\alpha$ ),  $\sigma_A$  is the scatter in the A variable and  $\sigma_B$  is the scatter in the B variable. All the scatter values in the table are expressed in dex, while all the errors are given at the 95% confidence level.



**Fig. 5.**  $L_X - L_{op}$  relation. in panel *a*) the filled triangles are the X-ray selected clusters of the RASS-SDSS sample of Paper III. In panel *b*) the filled points are the normal X-ray emitting Abell clusters, the empty triangles are the AXU clusters with a marginally significant X-ray detection, the empty squares are the AXU clusters with no detection. The solid line is the best fit obtained from the RASS-SDSS clusters. The optical luminosity is computed in the  $i$ -band.

should deviate from the relation. We quantify the presence of galaxy substructures in the whole Abell cluster sample through the Dressler & Shectman (1988) statistical test. This test looks for deviations of the local velocity mean and dispersion from the global values. Here we adopt the slightly modified version of the test introduced by Biviano et al. (2002). We call  $P_{DS}$  the probability that a cluster does *not* contain substructures ac-

cording to the Dressler & Shectman test. We find that the fraction of clusters with a probability  $> 0.90$  ( $P_{DS} < 0.1$ ) of having significant substructure is somewhat low, 20%, compared to the results of previous studies (e.g. Dressler & Shectman 1988; Biviano et al. 1997). This is not surprising. We remind the reader that the 137 Abell clusters in our sample are selected to be relatively isolated and free of major contaminations



**Fig. 4.** Distribution of the residuals along the  $\log(L_X)$  axis for the Abell clusters without secure X-ray detection with more than 20 spectroscopic members within 1 abell radius and with  $P_{DS} > 0.1$ . The residuals are defined as  $\Delta\log(L_X) = \log(L_{X,m}) - \log(L_{X,p})$ , where  $L_{X,m}$  is the measured cluster X-ray luminosity and  $L_{X,p}$  is the  $L_X$  predicted by the  $L_X - M_{200}$  X-ray relation.

along the line-of-sight (see section 2.1). Anyhow, as shown in Fig. 3 the cluster with values of  $P_{DS}$  lower than 0.1 have the largest negative residuals from the best fit line. When the 20% of clusters with high level of subclustering (together with the Abell systems with unsecure X-ray detection) are excluded from the linear regression, the best fit parameters and the scatter of the relation are consistent with the values found in the case of the RASS-SDSS cluster sample. Table 1 lists the results of this linear regression in the line corresponding to the  $A(P_{DS} > 0.1) + X$  - ray sample, which refers to the Abell clusters with  $P_{DS} > 0.1$  plus the RASS-SDSS systems.

In order to characterize the different behavior of the normal Abell Clusters and the Abell systems without secure X-ray detection, we analyse the distribution of the residuals of the Abell clusters relatively to the RASS-SDSS  $L_X - M_{200}$  relation, along the  $\log(L_X)$  axis. The residuals are defined as  $\Delta\log(L_X) = \log(L_{X,m}) - \log(L_{X,p})$ , where  $L_{X,m}$  is the measured cluster X-ray luminosity and  $L_{X,p} = 0.0776 M_{200}^{2.04}$  is the  $L_X$  predicted by the  $L_X - M_{200}$  relation (see Table 1). Hence, a negative value of the residual indicates that the cluster has a low X-ray luminosity for its mass.

Panel e) of Fig.2 shows the distribution of the residuals of the normal Abell clusters. The median of the distribution is at  $-0.3 \pm 0.3$  and it moves to  $-0.1 \pm 0.3$  when the clusters with high level of subclustering are excluded. This confirms that those systems obey the same  $L_X - M_{200}$  relation as the RASS-SDSS clusters.

Panel f) of Fig.2 shows the same distribution for the Abell clusters without secure X-ray detection (except clusters with zero  $L_X$ ). The median of the distribution is at  $-0.9 \pm 0.4$ , which gives an indication that those clusters are *not* on the same  $L_X - M_{200}$  relation. 70% of those systems have an X-ray luminosity which is more than 3 times lower than what expected at their mass and 50% of them have  $L_X$  one order of magnitude lower than the expectation. Hence, the Abell Clusters without secure X-ray detection appear to be clearly X-ray underluminous for their mass. What causes this effect? Are those systems real clusters? The poor significance of the X-ray detection of these systems would suggest that it's a question of spurious detections in the redshift distribution. That is, the observed 3D galaxy overdensity of those systems is not due to a unique massive cluster but to the superposition of two interacting small groups. In fact, in this case a double peaked velocity distribution of the two systems could be missclassified as a unique Gaussian distribution with a large velocity dispersion. As a consequence the low X-ray luminosity of the two groups would be associated to the mass of a spurious massive cluster. To check this possibility we perform several tests. A doubled peak velocity distribution missclassified as a Gaussian should appear as a platikurtic distribution (more flat-topped than a Gaussian). This effect can be quantified with the the robust Tail Index (T.I. hereafter, Beers et al. 1991). Values of the T.I. larger than unity indicate a leptokurtic distribution (i.e. more centrally peaked than a Gaussian), while values smaller than unity indicate a platikurtic distribution. Values close to unity indicate a consistency with a Gaussian distribution. First, we compute the T.I. values of the individual cluster velocity distributions, for those clusters with unsecure X-ray detection with at least 10 member galaxies within  $r_{200}$ . 37 out of 51 systems fulfill this requirement. 3 out of 37 have platikurtic distributions and 1 has a leptokurtic one, while all the remaining distributions are consistent with a Gaussian. The confidence level used in the test is the 99%. Therefore, less than 10% of the clusters are suspected spurious detection. We perform the same analysis on the normal Abell clusters finding the same percentage of platikurtic distributions.

As a further test we use the Dressler & Shectman parameter to estimate the level of subclustering of those objects. Also this test is sensitive to the presence of different peaks in the redshift distribution and could reveal misclassifications. Only 5 clusters out of 51 systems without secure X-ray detection have values of  $P_{DS}$  lower than 0.1 (they comprise the 3 clusters with T.I. lower than 1). Hence the fact that a cluster is detected or not in X-ray does not seem to be related to subclustering in the distribution of cluster galaxies.

An additional cause of uncertainties in the mass estimation is the use of a small number of spectroscopic members in the measurement. To check this point, we perform the analysis of the residuals along the  $\log(L_X)$  axis for the systems with a high number of members. Fig. 4 shows the distribution of the residuals along the  $\log(L_X)$  axis for the Abell clusters without secure X-ray detection with more than 20 spectroscopic members within 1 Abell radius and with  $P_{DS} > 0.1$ . The mass estimation of these clusters with a high number of member galaxies should be less affected by the systematicis considered so far. The fact



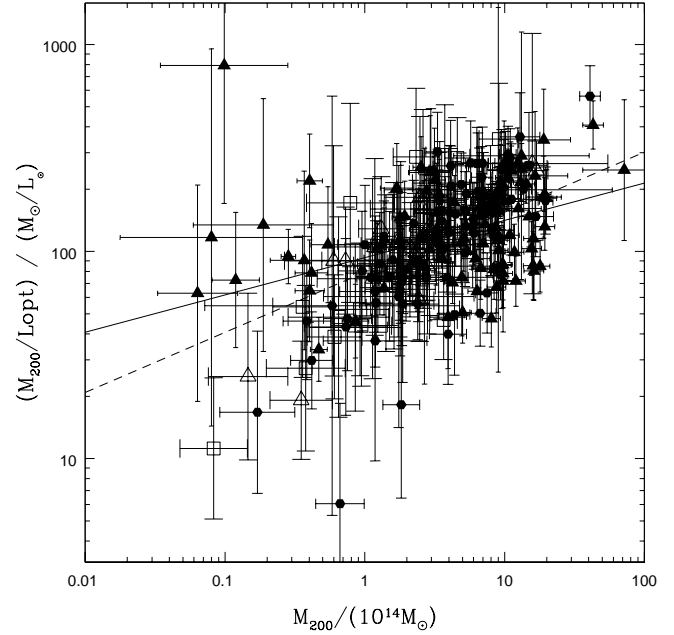
that the distribution still peaks at  $-1.0 \pm 0.3$  confirms that these systems do not lie on the RASS-SDSS  $M-L_X$  relations and that they are on average one order of magnitude fainter in the X-ray band than what is expected for their mass. Moreover, in the paper III of this series (Popesso et al. 2005b) we show that in the case of low level of subclustering the masses obtained from the dynamical analysis of the cluster members are consistent with the hydrodynamical mass estimates.

On the basis of these analyses we conclude that the Abell clusters without secure X-ray detection are not spurious objects and that their difference with regard to the normal Abell systems and the RASS-SDSS clusters is physical. Due to their location with regard to the X-ray  $M-L_X$  relation these objects are on average one order of magnitude fainter than what is expected for their mass. Their marginal detection or non-detection in X-rays suggests that RASS is too shallow to reveal the (probably weak) X-ray emission of these systems. Moreover, the detection depends on parameters not related to the cluster properties like local RASS exposure, galactic  $N_H$ , and cluster distance. This conclusion is supported by the fact that several of these underluminous X-ray clusters are confirmed to be very faint X-ray systems by other, independent analyses (Donahue et al. 2002, Ledlow et al. 2003), based on RASS PSPC pointed observations with longer exposure times. For these reasons a better physical distinction between these systems and the normal Abell clusters is the underluminosity in X-rays of the cluster compared to the RASS-SDSS relation. However, since the errors on  $L_X$  for these clusters is so large our chosen subdivision is more practical. We call these objects Abell X-ray Underluminous Clusters (AXU Clusters for short) throughout the paper.

### 3.2. The $L_X - L_{op}$ and the $L_{op} - M$ relations

Panel *a*) of Fig. 5 shows the  $L_X - L_{op}$  relation for the RASS-SDSS clusters (the optical luminosity is computed in the *i*-band). Panel *b*) of the same figure shows the  $L_X - L_{op}$  relation for the Abell sample. Similarly to what was found for the  $L_X - M_{200}$  relation, the best-fit regression lines obtained using the RASS-SDSS sample, or the combined RASS-SDSS and Abell samples, are not significantly different (see Table 1). Also in this case, the inclusion of the Abell clusters increases the scatter in the fitted relation. The AXU clusters are the main source of scatter but also the normal Abell clusters with high level of subclustering contribute to increase the scatter. The AXU clusters are significantly offset from the RASS-SDSS  $L_X - L_{op}$  relation, while the normal Abell clusters are not. The mean residual of the normal Abell clusters along the  $\log(L_{op})$  axis is  $0.12 \pm 0.25$ , while that of the AXU clusters is  $0.54 \pm 0.20$ . Thus, the AXU clusters are significantly underluminous in X-ray at given optical luminosity compared to both the normal Abell clusters and the X-ray selected RASS-SDSS systems.

Panel *a*) of Fig. 6 shows the  $L_{op} - M_{200}$  relation for the RASS-SDSS sample. Table 1 lists the best fit parameters obtained performing a linear regression in the logarithmic space. Note that the slope of the relations and their scatter are not

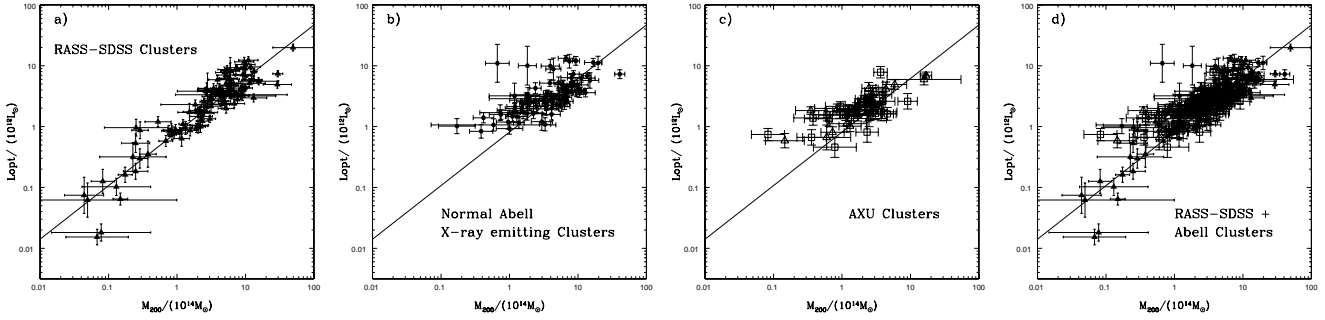


**Fig. 7.** The mass to light ratio versus the mass in the Sloan *i* band. The filled points are the normal Abell clusters, the empty triangles are the AXU clusters with a marginally significant X-ray detection, the empty squares are the AXU clusters without X-ray detection, the filled triangles are the X-ray selected clusters of the RASS-SDSS galaxy cluster sample of paper III. The solid line is the best fit obtained from the RASS-SDSS clusters, and the dashed line is the best fit obtained from the Abell plus the RASS-SDSS clusters.

significantly different in other SDSS bands compared to the *i*-band. Panels *b*) and *c*) of Fig. 6 show the location of the normal Abell clusters and, respectively, of the AXU clusters, relatively to the RASS-SDSS sample best fit line. Clearly, both the normal Abell clusters and the AXU clusters obey the same  $L_{op} - M_{200}$  relation as the X-ray selected clusters. The mean residual from the RASS-SDSS relation is  $\sim 0$  for both Abell clusters samples. Panel *d*) of Fig. 6 shows that adding the Abell clusters to the sample of RASS-SDSS clusters does not alter the slope and the scatter of the relation (see also Table 1). The slope of the  $L_{op} - M_{200}$  relation is confirmed to be smaller than 1. Therefore, we confirm the result of Paper III that the cluster mass-to-light ratio  $M/L$  is an increasing function of the cluster mass, as shown in Fig. 7.

### 4. Nature of the AXU clusters

As shown in the previous section, the AXU clusters are not a source of scatter in the  $L_{op} - M_{200}$  relation and, therefore, their optical luminosity does not differ from that of the normal X-ray emitting clusters of the same mass. On the other hand, they are significantly offset from the  $L_X - L_{op}$  and  $L_X - M_{200}$  relations. In this section we try to elucidate the physical reason of this, in what respect are the AXU clusters different from normal X-ray emitting galaxy clusters. For this purpose, here-



**Fig. 6.**  $L_{op} - M_{200}$  relation. Panel *a*) shows the  $L_{op} - M_{200}$  of the X-ray selected RASS-SDSS cluster sample (filled triangles). Panel *b*) shows the location of the Normal X-ray emitting Abell Clusters (filled dots) relatively to the best fit obtained in the X-ray selected sample. Panel *c*) shows the behaviour of the AXU systems in the same relation. The empty squares are the AXU clusters with marginally significant X-ray emission and the empty triangles are the totally underluminous AXU clusters. Panel *d*) shows the  $L_{op} - M_{200}$  relation for the RASS-SDSS plus the whole Abell sample. Symbols in this panel have the same meaning as in the previous three panels. The solid line in all 4 panels is the best fit line obtained in the X-ray selected sample of panel *a*). The optical luminosity is computed in the *i*-band.

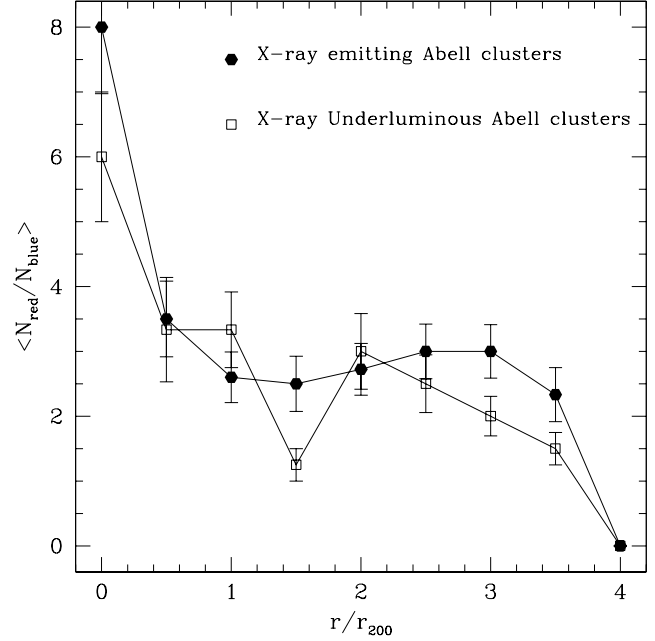
after we compare the galaxy luminosity functions, the relative fractions of red and blue galaxies, galaxy number density profiles, and velocity distributions, of AXU and normal clusters. We also look for the presence of optical substructures, in order to see whether AXU clusters are more unrelaxed systems than normal clusters.

#### 4.1. Luminosity functions

We use the SDSS photometric data to compute a composite galaxy luminosity function (LF) for the AXU systems, by stacking the individual cluster LFs calculated within  $r_{200}$ . The individual LFs are obtained by subtracting the field number counts calculated within an annulus around the cluster, from the number counts in the cluster region, as described in Paper II. In analogy to Paper IV, we have distinguished between early and late type galaxies using a colour cut at  $u - r = 2.22$ , as suggested by Strateva et al. (2001). Fig. 8 shows the composite LF of the AXU clusters (the filled points) for the whole (left-hand panel), the red (middle panel), and the blue (right-hand panel) cluster galaxy populations. For comparison we also plot the corresponding composite LFs of the normal Abell clusters (the empty squares), suitably renormalised in order to ease the comparison with the LFs of the AXU clusters. The solid lines in the three panels of Fig. 8 are the best fit double Schechter functions, obtained in Paper IV on the corresponding populations of the X-ray selected RASS-SDSS galaxy clusters. It is clear that there are no significant differences among the LFs of the three cluster samples, for any of the galaxy populations.

#### 4.2. Blue galaxy fractions

In order to study the relative fraction of blue and red galaxies in the different cluster samples, we stack together the galaxy colour distributions of all the clusters of each given sample. Note that in this case we only consider spectroscopically confirmed cluster members, down to an absolute Petrosian magni-

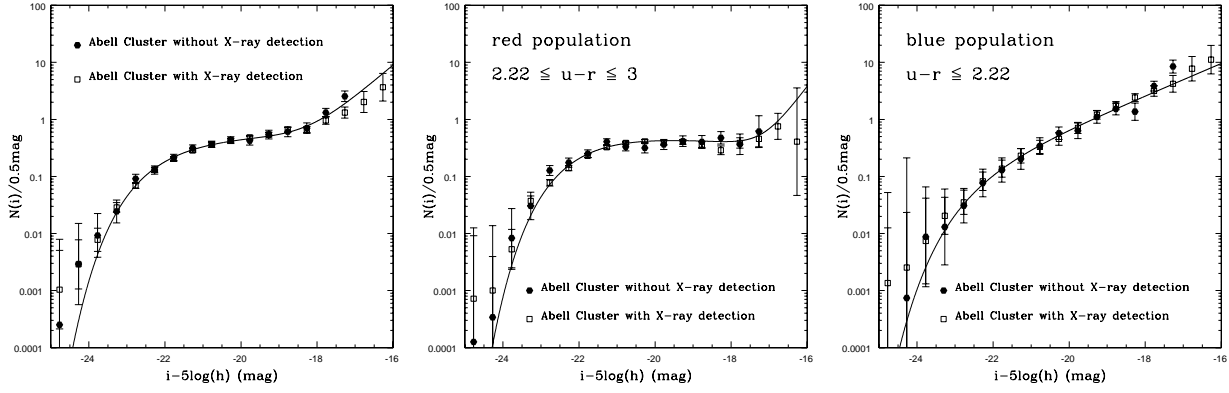


**Fig. 9.** The ratio of the numbers of red and blue cluster galaxies as a function of the clustercentric distance in units of  $r_{200}$ .

tude  $r_{Petro} \leq -20$ , and within  $1.5 r_{200}$ . We find that there is no difference between the global colour distributions of the normal Abell clusters and the AXU clusters. AXU clusters do seem to have a larger fraction of blue galaxies than normal Abell clusters in the outer regions (see Fig. 9), but the statistical significance of this difference is marginal.

#### 4.3. Galaxy number density profiles

In analogy to the analyses presented above, we compute the composite galaxy number density profiles of the AXU clusters



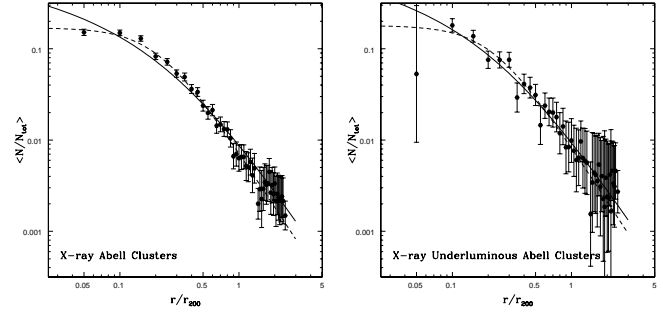
**Fig. 8.** The luminosity function of the normal Abell clusters and the AXU clusters. Left panel: composite cluster LFs of the whole galaxy population; filled dots, AXU clusters; open squares, normal Abell clusters; solid line, best-fit double Schechter LF obtained on the X-ray selected RASS-SDSS cluster sample (see Paper IV). Middle panel: same as left panel, but for the red galaxies only ( $u - r \geq 2.22$ ). Right panel: same as left panel, but for the blue galaxies only ( $u - r < 2.22$ ).

and the normal Abell clusters. These are shown in Fig. 10. In order to characterize these profiles, we fit two models to them. One is a King (1966) profile,  $\Sigma(x) = \Sigma_0(1 + x^2)^{-1}$ , where  $x = r/r_c$  and  $r_c$  is the core radius. The other model is the projected NFW profile, which in 3-dimensions reads  $n(x) = n_0 x^{-1}(1 + x^2)^{-1}$ , where  $x = c_g r/r_{200}$  and  $c_g$  is the concentration parameter. The surface density is then an integral of the three-dimensional profile (see Bartelmann 1996 for more details).

For both the AXU and the normal Abell cluster samples the composite radial profiles are better fit by a King profile (according to a standard  $\chi^2$  test). This is in agreement with previous results in the literature (Adami et al. 1998b; Díaz et al. 2005). The best fit values of the core radii for the two samples of clusters are  $r_c/r_{200} = 0.209 \pm 0.006$  Mpc (normal Abell clusters) and  $r_c/r_{200} = 0.218 \pm 0.009$  Mpc (AXU clusters). Therefore the two profiles are perfectly consistent. However, we note that in the case of the AXU clusters also a NFW profile provides an acceptable fit to the data. This is however not due to a more cuspy profile than that of the normal Abell clusters, but to the large error bar in the first bin of the number density profile. Such a large error bar is due to a paucity of galaxies in the very centre of AXU clusters. Hence AXU clusters, relative to normal Abell clusters, seem to have a lower central density of galaxies. This is consistent with their larger fraction of blue galaxies (see the previous section) when we convolve this information with the morphology-density relation (Dressler 1980).

#### 4.4. Galaxy velocity distributions

In this subsection we analyze the composite galaxy velocity distributions of the AXU clusters and the normal X-ray emitting clusters. The differences between the mean cluster velocity and the velocities of its member galaxies are normalized by  $\sigma_c$ , the global cluster velocity dispersion. Each individual cluster velocity distribution is then normalized to the total number of cluster members in the considered cluster region. We consider only member galaxies with absolute Petrosian magnitude  $r_{Petro} \leq -20$  mag, which is brighter than any cluster limiting



**Fig. 10.** The composite galaxy number density profiles of the normal Abell clusters (left panel) and of the AXU clusters (right panel). The solid and dashed lines are the best fits given by a projected NFW, and, respectively, a King density profile.

magnitude. We estimate the incompleteness of clusters spectroscopic samples by comparing the number of cluster spectroscopic members found within  $3.5 r_{200}$  and within the chosen absolute magnitude limit, with the number of cluster members obtained from the photometric data. The photometric sample is not affected by incompleteness down to the chosen magnitude limit. The number of photometric cluster members is obtained by subtracting the number of background galaxies at the same magnitude limit, rescaled by the cluster area, from the number of galaxies (cluster+field) in the cluster region. From this analysis we conclude that all the clusters have a spectroscopic completeness  $\geq 80\%$  down to  $r_{Petro} \leq -20$  mag.

Fig. 11 shows the composite cluster velocity distributions of the normal Abell clusters and the AXU clusters, for two clustercentric distance intervals,  $r/r_{200} \leq 1.5$  ('inner' sample hereafter), and  $1.5 < r/r_{200} \leq 3.5$  ('outer' sample hereafter). The best-fit Gaussians are overplotted as dashed lines. The best-fit Gaussian dispersion decreases from  $1.00 \pm 0.01$  to  $0.96 \pm 0.02$  from the inner to the outer velocity distribution of the normal Abell clusters. The decrease is much stronger for the AXU clusters, from  $1.00 \pm 0.05$  to  $0.80 \pm 0.07$ . Hence, the veloc-

ity dispersion profile is much steeper for the AXU clusters than for the normal Abell clusters. It is reminiscent of the steep velocity dispersion profile of late-type cluster galaxies (Biviano et al. 1997; Adami et al. 1998c; Biviano & Katgert 2004).

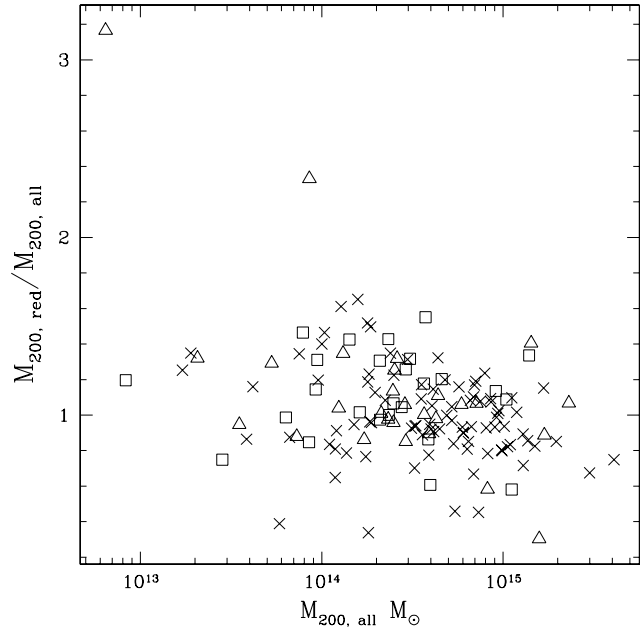
In order to gain more insight into the meaning of this result, we consider statistics that address the *shape* of the velocity distributions. A classical shape estimator, the kurtosis, is not recommended because it is very much influenced by the tails of the distribution. Instead, we consider the more robust T.I.. The values of the scaled tail index for the considered distribution are 1.05, 0.88, 1.16, 1.45 for the four subsamples (inner normal, outer normal, inner AXU, outer AXU, respectively). As explained above, values larger than unity indicate a leptokurtic distribution (i.e. more centrally peaked than a Gaussian), while values smaller than unity indicate a platikurtic distribution (i.e. more flat-topped than a Gaussian). Only the scaled tail index value 1.45 is significantly different from unity at  $> 99\%$  confidence level. We conclude that the outer velocity distribution of the AXU clusters is not only significantly narrower than all other velocity distributions, but it is also significantly non-Gaussian, leptokurtic in particular. Leptokurtic velocity distributions occur in the outer cluster regions when the external cluster members are characterized by radially elongated orbits (Merritt 1987; van der Marel et al. 2000). Cosmological simulations predict that halos should display leptokurtic velocity distributions in their infall regions, characterized by ordered flows (Wojtak et al. 2005).

In order to estimate the amount of radial anisotropy required to fit the shape of the outer velocity distribution of AXU clusters, we determine the value of the Gauss-Hermite (GH hereafter) moment of order four (see, e.g., van der Marel et al. 2000). For completeness we determine the GH moments also for the velocity distributions of the other three subsamples. As expected from the T.I. analysis above, the GH polynomial fits to the velocity distributions of the normal Abell cluster galaxies, and of the inner AXU cluster galaxies, are very similar to the Gaussian fits, and only for the velocity distribution of the outer AXU cluster galaxies there is a clear difference between the GH polynomial fit and the Gaussian fit (see Fig. 11).

We then compare the values of the 4<sup>th</sup> GH moments of these velocity distributions with the predictions of the dynamical models of van der Marel et al. (2000, see their Figure 8). While these predictions do depend on the number density distribution of the considered galaxy population, such a dependence is not strong. Hence, direct comparisons with van der Marel et al. dynamical models should provide useful informations on the orbital anisotropy of the galaxy populations.

The 4<sup>th</sup> order GH moments are  $-0.018$  and  $-0.012$ , for the inner and outer velocity distributions of normal Abell cluster galaxies, respectively, and  $0.002$  and  $0.106$  for the inner and outer velocity distributions of AXU cluster galaxies, respectively. These values are all consistent with isotropic orbits, except that of the outer velocity distribution of the AXU cluster galaxies. For this population, we find  $\sigma_r/\sigma_t \sim 2$  where  $\sigma_r$  and  $\sigma_t$  are the radial and tangential velocity dispersions of the galaxy population.

The analysis of the galaxy velocity distributions reveals a clear difference between normal Abell clusters and AXU clusters.



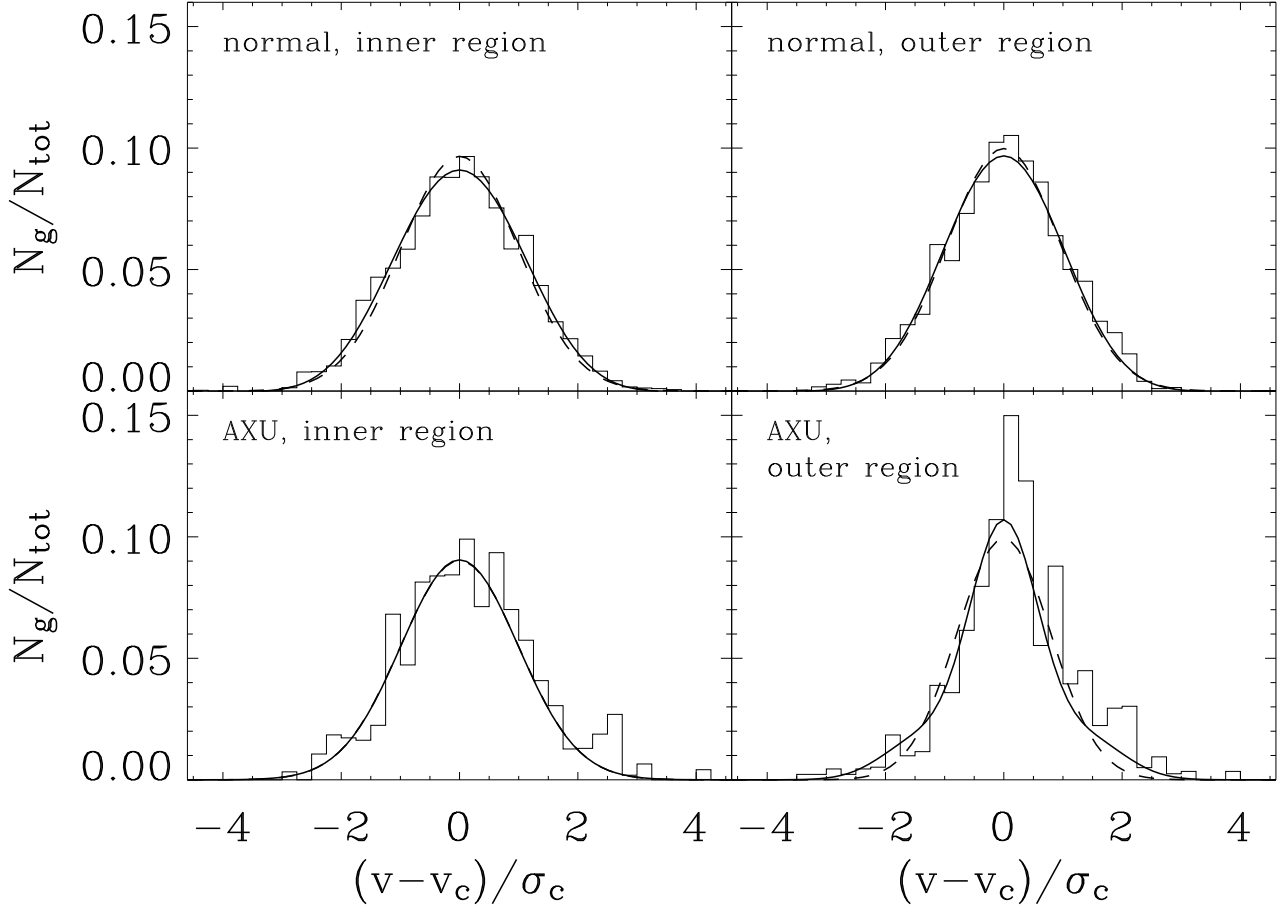
**Fig. 12.** Ratio of  $M_{200}$  calculated only with the cluster red galaxy members ( $M_{200,red}$ ) and  $M_{200}$  calculated with all the cluster members ( $M_{200,all}$ ) versus  $M_{200,all}$ . The crosses are the 'normal' Abell clusters, the empty triangles and squares are the AXU systems with marginally significant and without X-ray detection, respectively.

The characteristics of the velocity distribution of AXU cluster galaxies is reminiscent of an infalling galaxy population, such as the one seen in numerical simulations in the external regions of dark matter haloes (Wojtak et al. 2005). The higher fraction of blue galaxies seen in AXU clusters, relative to that seen in normal Abell clusters, is certainly consistent with a higher fraction of infalling galaxies, since these must be part of the field galaxy population.

## 5. Discussion and Conclusions

We have studied the X-ray and optical properties of 137 isolated Abell clusters. Each object has a confirmed three-dimensional overdensity of galaxies. We have looked for the X-ray counterpart of each system in the RASS data. Three classes of objects have been identified, where the classification is based on the quality of the X-ray detection. 86 clusters out of the 137 Abell systems have a clear X-ray detection and are considered normal X-ray emitting clusters (the 'normal Abell clusters'). 27 systems have a X-ray detection of low significance (less the  $3\sigma$ ) and 24 do not have clear X-ray detection (a rough estimate of  $L_X$  is provided but with huge statistical errors).

The normal Abell clusters follow the same scaling relations observed in the X-ray selected RASS-SDSS clusters. The 24 + 27 Abell clusters with unsecure X-ray detection appear to be outliers in the  $L_X - M_{200}$  relation determined for X-ray luminous clusters. Their X-ray luminosity is on average one order of magnitude fainter than would be expected for their mass. A



**Fig. 11.** The composite cluster velocity distributions. Top-left panel: the velocity distribution of galaxies in normal Abell clusters (histogram), within  $1.5 r_{200}$ . Top-right panel: the velocity distribution of galaxies in normal Abell clusters (histogram), at clustercentric distances in the range  $1.5\text{--}3.5 r_{200}$ . Bottom-left panel: the velocity distribution of galaxies in AXU clusters (histogram), within  $1.5 r_{200}$ . Bottom-right panel: the velocity distribution of galaxies in AXU clusters (histogram), at clustercentric distances in the range  $1.5\text{--}3.5 r_{200}$ . In each panel, the dashed line represents the best-fit Gaussian, and the solid line the best-fit obtained with a GH polynomial of order 4.

careful analysis of the 3D galaxy overdensity of these systems reveals that the individual galaxy velocity distributions in the virial region are gaussian in 90% of the clusters and are not ascribable to the superposition of smaller interacting systems. We conclude that these Abell cluster with unsecure X-ray detection in RASS are not spurious detections in the redshift distribution, but are a distinct class of objects. Due to their location with regard to the RASS-SDSS  $M\text{--}L_X$  relation we call them ‘Abell X-ray underluminous clusters’ or AXU clusters for short. Several AXU clusters are confirmed to be very faint X-ray objects in the literature. Their X-ray flux is probably too low to be detected in the RASS survey. Yet, AXU clusters are not outliers from the  $L_{op} - M_{200}$  relation, i.e. they have a normal optical luminosity given their mass. Hence, the distinctive signature of AXU clusters seems to lie in an X-ray luminosity which is unexpectedly low.

We have looked for other properties of AXU clusters that make them different from normal Abell clusters. We have

shown that AXU clusters do not have more substructures than normal Abell clusters. The galaxy luminosity functions within the virial region of the two cluster samples are very similar to each other. Rather similar are their galaxy number density profiles, even if the AXU clusters seem to lack galaxies near the core, relative to normal Abell clusters (but the significance of this result is low). The fractions of blue galaxies in the two kinds of clusters are only marginally different, AXU clusters being characterized by a higher fraction.

The main difference between the two classes of objects lies in the velocity distribution of their member galaxies. The galaxy velocity distribution of the normal Abell clusters is perfectly fitted by a Gaussian both in the inner, virialized region ( $\leq 1.5 r_{200}$ ), and also in the external region ( $1.5 r_{200} \leq r \leq 3.5 r_{200}$ ). The AXU clusters instead have a Gaussian velocity distribution only within the virial region. In the external region, their velocity distribution is significantly more peaked than a Gaussian. The analysis of its shape by comparison with dy-

namical models available in the literature (van der Marel et al. 2000), suggests a radially anisotropic galaxy orbital distribution. However, the galaxies in this external region need not be in dynamical equilibrium with the cluster potential. As a matter of fact, a leptokurtic shape of the velocity distribution is a typical signature of the external, infall regions of dark matter haloes (Wojtak et al. 2005).

The analysis of the velocity distribution of the AXU clusters in their outer regions hence suggests the presence of an unvirialized component of the galaxy population, still in the process of accretion onto the cluster. This infalling population would be mainly composed of field, hence blue, galaxies, which could then explain the excess of blue galaxies in AXU clusters, relative to normal Abell clusters. On the other hand, the Gaussian velocity distribution in the inner region suggests that there the galaxy population is dynamically more evolved, and probably virialized.

By a similar analysis on a different sample of X-ray underluminous clusters, Bower et al. (1997) came to propose two different scenarios. AXU clusters could be severely affected by projection effects arising from surrounding large-scale structure filaments elongated along the line-of-sight. Their velocity dispersion, and hence their virial masses would then be severely overestimated by interlopers in the filaments. In the alternative scenario AXU clusters could be clusters not yet formed, or in the phase of forming, or, at least, caught at a particular stage of their evolution, while they are undergoing a rapid mass growth.

Should the former of the two scenarios apply, we would expect AXU clusters to be X-ray underluminous for their mass, but they could still be optically luminous because we partly see the light of the filament projected onto the cluster. However, contamination by interlopers does affect the optical luminosity estimate, but not so much as the virial mass estimate, and not so much in the  $i$  band, where contamination by the field (hence blue) galaxies should be small. Therefore, in such scenario it would be surprising that the clusters obey so well the  $L_{op} - M_{200}$  relation, which requires that the effects of the filament on the dynamical mass estimate and the optical light in the aperture both conspire not to produce an offset from the relation. It would also be surprising that the AXU clusters show a galaxy LF perfectly consistent with the steep LF found in galaxy clusters (see Popesso et al. paper II and IV) and not the flat LF observed in the field (Blanton et al. 2005). Instead AXU clusters are not outliers from the  $L_{op} - M_{200}$  relation. If anything, AXU clusters are overluminous in the optical for their mass. In fact, the biweight-average (see Beers et al. 1990)  $i$ -band mass-to-light ratios of normal Abell clusters and AXU clusters are  $150 \pm 10 M_{\odot}/L_{\odot}$ , and  $110 \pm 10 M_{\odot}/L_{\odot}$ , respectively.

As a further test, we have re-calculated the virial masses of all clusters by considering only red cluster members belonging to the red sequence in the  $u - i$  vs.  $i$  color-magnitude diagram. In this way contamination by interlopers is strongly reduced (see, e.g., Biviano et al. 1997). Masses computed using all cluster members are compared to masses computed using only red-sequence members in Fig. 12. The cluster masses do not change significantly when only red-sequence members are

used to calculate them, suggesting a low level of contamination by interlopers.

The results of our analyses therefore support Bower et al.'s alternative scenario, namely AXU clusters are systems in the stage of formation and/or of significant mass accretion. If AXU clusters are still forming, the intra-cluster gas itself may still be infalling or have not yet reached the virial temperature. In addition, for AXU clusters undergoing massive accretion, it is to some degree possible that the continuous collisions of infalling groups is affecting the gas distribution, lowering its central density (such as in the case of the so called 'bullet cluster', see Barrera et al. 2002 and Clowe et al. 2004). In both cases the X-ray luminosity would be substantially lower than predicted for the virial mass of the system, because of its dependence on the square of the gas density. We note however that a virialized cluster undergoing a strong collision with an infalling group would show up as a substructured cluster, yet the AXU clusters do not show an increased level of substructures when compared to normal Abell clusters. In summary, we know that the X-ray emission is very much dominated by the central region whereas the optical properties are more global. Therefore it could well be that we see a rough relaxation on the large scale (within  $1.5r_{200}$ ) of the galaxy system reflected by a rough Gaussian galaxy velocity distribution, while the central region has not yet settled to reach the high density and temperatures of the luminous X-ray clusters.

In order to explore this further, we need much more detailed information on the distribution of the density and temperature of the intracluster gas in AXU clusters, something that cannot be done with the RASS data, but requires the spatial resolution and sensitivity of XMM-Newton.

Our results give supports to the conclusion of Donahue et al. (2002) concerning the biases inherent in the selection of galaxy clusters in different wavebands. While the optical selection is prone to substantial projection effects, also the X-ray selection is not perfect or not simple to characterize. The existence of X-ray underluminous clusters, even with large masses, makes it difficult to reach the needed completeness in mass for cosmological studies. Moreover, as discussed in Paper III, the relation between the X-ray luminosity and mass is not very tight even for the X-ray bright clusters, and the relation between cluster masses and optical luminosities is as tight or perhaps even tighter. Clearly, a multi-waveband approach is needed for optimizing the completeness and reliability of clusters samples.

On the other hand, it becomes clear that for precision cosmology we also need a more observationally oriented prescription of cluster selection from theory, rather than a mere counting of "relaxed" dark matter halos. Predicted distribution functions closer to the observational parameters like temperature or velocity dispersion distribution functions and their relations to X-ray and optical luminosity are needed.

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## Appendix A: The Abell Cluster Catalog

Here we list the properties of the 137 spectroscopically confirmed Abell systems extracted from the SDSS DR3, used in this paper. The meaning of the individual columns is the following:

- column 1: the name of the Abell cluster
- column 2: the number of cluster members within 1 Abell radius
- column 3: the cluster mean redshift
- column 4: the cluster velocity dispersion and its error
- column 5: the cluster mass within  $r_{200}$ ,  $M_{200}$ , in units of  $10^{14} M_{\odot}$
- column 6: the cluster mass within  $r_{200}$  calculated using only the cluster red members,  $M_{200,\text{red}}$ , in units of  $10^{14} M_{\odot}$ ;  $M_{200,\text{red}}$  is given only for the clusters with at least 10 red members
- column 7: the fractional error on  $M_{200}$  and  $M_{200,\text{red}}$
- column 8: the cluster virial radius,  $r_{200}$ , in Mpc
- column 9: the cluster optical luminosity  $L_{\text{op}}$  and its error, in unit of  $10^{12} L_{\odot}$
- column 10: the cluster X-ray luminosity in the ROSAT energy band (0.1-2.4 erg s $^{-1}$ ), in unit of  $10^{44}$  erg s $^{-1}$
- column 11: the fractional error on the X-ray luminosity
- column 12: the Dressler & Shectman probability that a cluster does not contain substructures,  $P_{DS}$  (values < 0.1 indicate clusters that are likely to contain substructures)
- column 13: the X-ray class: 0 for the normal X-ray emitting cluster, 1 for the Abell systems with less the  $3\sigma$  X-ray detection, 2 for the X-ray non-detected Abell Clusters.

Name	$N_{\text{mem}}$	$z_c$	$\sigma_c$	$M_{200}$	$M_{200,\text{red}}$	$er_M$	$r_{200}$	$L_{\text{op}}$	$L_X$	$er_{L_X}$	$P_{DS}$	X-class
a0116	24	0.0661	$582 \pm 73$	4.66	4.71	0.29	1.6	$1.59 \pm 0.35$	0.090	0.25	0.19	0
a0117	95	0.0550	$559 \pm 41$	4.03	3.85	0.15	1.5	$2.52 \pm 0.64$	0.064	0.26	0.96	0
a0129	19	0.1501	$749 \pm 119$	8.78	9.80	0.36	2.0	$5.03 \pm 1.87$	0.548	0.26	0.62	0
a0130	21	0.1106	$447 \pm 84$	2.81	2.34	0.37	1.4	$2.12 \pm 0.48$	0.161	0.61	0.13	1
a0152	69	0.0589	$729 \pm 59$	7.04	5.12	0.19	1.8	$2.38 \pm 0.52$	0.057	0.25	0.09	0
a0168	110	0.0450	$559 \pm 36$	3.57	2.89	0.14	1.5	$2.70 \pm 0.36$	0.370	0.09	0.57	0
a0175	37	0.1285	$606 \pm 60$	4.47	3.73	0.31	1.6	$9.88 \pm 2.53$	1.114	0.29	0.84	0
a0190	17	0.1021	$431 \pm 122$	2.19	0.61	0.66	1.2	$1.64 \pm 0.41$	0.034	0.70	0.00	0
a0208	31	0.0793	$499 \pm 60$	2.60	2.42	0.29	1.3	$1.64 \pm 0.32$	0.237	0.22	0.68	0
a0243	32	0.1125	$469 \pm 50$	2.52	2.04	0.30	1.3	$2.83 \pm 0.39$	0.000	0.00	0.40	1
a0315	16	0.1740	$636 \pm 96$	6.61	6.24	0.41	1.8	$4.91 \pm 0.91$	0.056	1.20	0.50	2
a0351	14	0.1108	$510 \pm 118$	2.70	2.27	0.42	1.3	$2.35 \pm 0.57$	0.016	1.50	0.99	2
a0412	31	0.1092	$585 \pm 50$	3.29	3.04	0.28	1.4	$2.20 \pm 0.69$	0.071	0.53	0.11	2
a0441	25	0.1443	$907 \pm 554$	17.17	4.80	1.25	2.5	$5.95 \pm 1.24$	0.218	0.44	0.00	2
a0607	34	0.0962	$501 \pm 88$	2.88	2.65	0.37	1.4	$2.61 \pm 0.42$	0.023	0.57	0.56	1
a0620	14	0.1323	$518 \pm 76$	2.17	2.78	0.61	1.2	$3.34 \pm 0.91$	0.787	0.17	0.35	0
a0626	15	0.1168	$757 \pm 158$	7.16	5.48	0.40	1.8	$3.30 \pm 0.83$	0.092	0.44	0.32	0
a0628	61	0.0834	$642 \pm 63$	5.98	4.46	0.19	1.7	$2.81 \pm 0.44$	0.208	0.35	0.81	0
a0631	48	0.0826	$577 \pm 48$	3.77	3.11	0.19	1.5	$1.09 \pm 0.27$	0.061	0.42	0.49	0
a0646	29	0.1266	$738 \pm 96$	10.45	9.72	0.24	2.1	$3.82 \pm 0.80$	2.487	0.09	0.92	0
a0655	47	0.1276	$736 \pm 78$	9.47	9.21	0.20	2.0	$7.29 \pm 0.94$	2.527	0.16	0.88	0
a0660	26	0.0642	$752 \pm 138$	7.91	7.61	0.43	1.9	$1.62 \pm 0.32$	0.000	0.00	0.27	2
a0667	17	0.1441	$512 \pm 85$	2.05	1.33	1.25	1.2	$2.88 \pm 0.63$	1.998	0.11	0.53	0
a0682	17	0.1147	$266 \pm 242$	0.75	0.22	2.12	0.9	$1.07 \pm 0.25$	0.057	0.50	0.57	0
a0685	16	0.1464	$496 \pm 56$	4.47	3.49	0.26	1.6	$3.46 \pm 0.88$	0.000	0.00	0.07	2
a0714	29	0.1392	$574 \pm 78$	4.97	4.86	0.26	1.6	$4.16 \pm 1.10$	0.041	0.83	0.86	2
a0716	17	0.1188	$494 \pm 144$	2.88	2.37	0.59	1.4	$1.36 \pm 0.43$	0.009	1.50	0.46	2
a0729	28	0.0978	$688 \pm 87$	3.38	3.90	0.36	1.4	$1.21 \pm 0.40$	0.232	0.22	0.19	0
a0733	11	0.1156	$392 \pm 78$	0.91	–	0.69	0.9	$1.69 \pm 0.51$	0.535	0.62	0.49	0
a0736	42	0.0619	$826 \pm 98$	10.11	9.08	0.29	2.1	$4.66 \pm 0.77$	0.061	0.25	0.04	0
a0847	16	0.1508	$704 \pm 115$	5.03	4.11	0.40	1.6	$2.94 \pm 0.54$	0.730	0.21	0.87	0
a0856	19	0.1393	$450 \pm 69$	1.92	2.61	0.48	1.2	$1.74 \pm 0.45$	0.407	0.38	0.01	0
a0860	31	0.0965	$941 \pm 95$	12.98	12.0	0.36	2.2	$2.13 \pm 0.46$	0.313	0.23	0.00	0
a0861	17	0.1259	$468 \pm 104$	3.29	2.88	0.44	1.4	$2.51 \pm 0.51$	0.237	0.27	0.67	1
a0866	10	0.1435	$266 \pm 106$	0.83	–	0.84	0.9	$1.34 \pm 0.39$	0.143	0.47	0.12	1

Name	$N_{mem}$	$z_c$	$\sigma_c$	$M_{200}$	$M_{200,red}$	$er_M$	$r_{200}$	$L_{op}$	$L_X$	$er_{L_X}$	$P_{DS}$	X-class
a0869	12	0.1198	$381 \pm 127$	1.74	2.02	0.66	1.2	$1.81 \pm 0.39$	0.241	0.30	0.29	1
a0892	23	0.0943	$470 \pm 148$	1.45	0.76	0.86	1.1	$3.20 \pm 1.56$	0.175	0.26	0.09	0
a0912	28	0.0906	$590 \pm 82$	3.72	3.05	0.31	1.5	$3.01 \pm 0.60$	0.021	0.62	0.75	0
a0917	11	0.1370	$403 \pm 76$	0.76	–	0.46	0.9	$1.57 \pm 0.37$	0.252	0.31	0.24	1
a0919	12	0.0954	$136 \pm 37$	0.21	–	0.66	0.6	$0.59 \pm 0.16$	0.033	0.55	0.18	2
a0933	56	0.0965	$455 \pm 46$	2.86	3.22	0.20	1.4	$4.28 \pm 0.89$	0.387	0.21	0.87	0
a0975	14	0.1192	$208 \pm 58$	0.48	–	0.50	0.8	$0.67 \pm 0.19$	0.068	0.50	0.96	1
a1038	13	0.1275	$253 \pm 48$	0.55	0.48	0.35	0.8	$1.40 \pm 0.27$	0.108	0.44	0.83	0
a1064	17	0.1318	$485 \pm 93$	2.30	2.21	0.34	1.3	$2.39 \pm 0.59$	0.211	0.33	0.74	0
a1066	100	0.0690	$731 \pm 52$	6.63	5.55	0.15	1.8	$4.15 \pm 0.60$	0.657	0.17	0.35	0
a1072	11	0.1173	$364 \pm 83$	1.45	–	0.67	1.1	$1.12 \pm 0.36$	0.029	0.86	0.10	2
a1076	18	0.1168	$418 \pm 77$	1.57	2.06	0.37	1.1	$1.46 \pm 0.30$	0.295	0.21	0.96	0
a1078	11	0.1242	$249 \pm 51$	0.50	–	0.66	0.8	$1.38 \pm 0.38$	0.182	0.37	0.60	1
a1092	26	0.1058	$449 \pm 64$	2.07	1.47	0.34	1.2	$1.55 \pm 0.35$	0.000	0.00	0.02	2
a1107	15	0.1508	$792 \pm 104$	10.03	10.3	0.33	2.1	$2.61 \pm 0.78$	0.265	0.38	0.03	1
a1132	27	0.1358	$880 \pm 138$	8.90	7.48	0.36	2.0	$6.37 \pm 0.95$	3.038	0.07	0.45	0
a1139	89	0.0395	$376 \pm 34$	1.68	1.07	0.19	1.2	$1.16 \pm 0.25$	0.136	0.16	0.24	0
a1143	13	0.1379	$459 \pm 86$	2.10	–	0.45	1.2	$2.25 \pm 0.56$	0.030	0.80	0.10	2
a1164	19	0.1057	$609 \pm 144$	4.24	5.79	0.54	1.6	$1.75 \pm 0.60$	0.074	0.61	0.15	1
a1171	16	0.0577	$161 \pm 40$	0.12	0.09	0.56	0.5	$0.74 \pm 0.17$	0.024	0.55	0.01	1
a1189	37	0.0969	$654 \pm 196$	4.58	4.26	0.59	1.6	$2.63 \pm 0.44$	0.087	0.32	0.20	0
a1205	80	0.0761	$865 \pm 73$	11.99	9.13	0.19	2.2	$3.88 \pm 0.54$	0.976	0.09	0.01	0
a1218	23	0.0801	$364 \pm 75$	0.91	0.63	0.39	0.9	$0.81 \pm 0.17$	0.017	0.56	0.58	2
a1221	11	0.1103	$289 \pm 132$	0.77	–	0.82	0.9	$0.66 \pm 0.32$	0.000	0.00	0.66	2
a1236	38	0.1021	$533 \pm 59$	3.72	2.27	0.29	1.5	$2.57 \pm 0.45$	0.150	0.30	0.06	0
a1302	47	0.1153	$691 \pm 80$	7.35	7.14	0.25	1.9	$3.61 \pm 1.08$	1.307	0.09	0.72	0
a1346	74	0.0983	$709 \pm 54$	7.64	4.59	0.18	1.9	$3.98 \pm 0.59$	0.208	0.30	0.15	0
a1364	41	0.1066	$553 \pm 59$	2.85	2.80	0.24	1.4	$4.27 \pm 0.94$	0.040	0.80	0.55	2
a1366	42	0.1164	$691 \pm 70$	7.72	8.13	0.20	1.9	$2.61 \pm 0.53$	1.550	0.10	0.88	0
a1368	27	0.1293	$735 \pm 92$	7.84	8.40	0.28	1.9	$3.71 \pm 0.65$	0.130	0.47	0.06	0
a1376	16	0.1179	$461 \pm 204$	3.11	3.43	0.88	1.4	$1.62 \pm 0.39$	0.013	0.67	0.31	2
a1387	35	0.1310	$692 \pm 73$	6.73	5.44	0.27	1.8	$4.91 \pm 0.66$	0.693	0.20	0.05	0
a1392	11	0.1361	$517 \pm 146$	3.86	–	0.61	1.5	$3.11 \pm 0.71$	0.707	0.19	0.49	0
a1399	23	0.0910	$251 \pm 59$	0.46	0.33	0.52	0.8	$1.83 \pm 0.27$	0.000	0.00	0.03	2
a1406	14	0.1170	$337 \pm 97$	1.48	0.96	0.59	1.1	$1.85 \pm 0.48$	0.207	0.47	0.31	0
a1407	10	0.1349	$561 \pm 142$	2.78	–	0.51	1.4	$2.64 \pm 0.50$	0.423	0.28	0.78	0
a1411	10	0.1327	$377 \pm 98$	1.41	–	0.92	1.1	$1.54 \pm 0.31$	0.056	0.67	0.44	2
a1419	19	0.1077	$504 \pm 89$	2.89	3.06	0.31	1.4	$2.14 \pm 0.50$	0.233	0.30	0.96	0
a1424	83	0.0754	$662 \pm 45$	5.49	4.88	0.14	1.7	$2.32 \pm 0.50$	0.476	0.13	0.13	0
a1437	33	0.1341	$1497 \pm 13$	39.89	30.5	0.17	3.2	$7.27 \pm 1.24$	3.461	0.08	0.12	0
a1456	35	0.1346	$540 \pm 54$	4.18	4.30	0.23	1.6	$7.82 \pm 1.72$	0.431	0.27	0.63	1
a1457	17	0.0626	$177 \pm 42$	0.29	0.27	0.61	0.6	$0.40 \pm 0.13$	0.000	0.00	0.29	2
a1468	49	0.0869	$361 \pm 92$	1.80	1.49	0.19	1.5	$1.86 \pm 0.94$	0.004	1.00	0.33	2
a1496	56	0.0958	$347 \pm 46$	1.53	1.29	0.30	1.1	$1.85 \pm 0.38$	0.033	0.50	0.00	2
a1501	15	0.1336	$406 \pm 57$	1.18	1.14	0.40	1.0	$1.19 \pm 0.32$	0.268	0.26	0.61	0
a1507	65	0.0600	$374 \pm 42$	1.36	0.92	0.23	1.1	$1.47 \pm 0.30$	0.072	0.24	0.76	0
a1516	72	0.0765	$705 \pm 71$	8.30	8.08	0.19	1.9	$11.88 \pm 3.12$	0.151	0.27	0.65	0
a1518	23	0.1065	$628 \pm 118$	4.49	2.40	0.41	1.6	$2.61 \pm 0.85$	0.182	0.23	0.14	1
a1539	17	0.1072	$510 \pm 60$	3.35	2.47	0.32	1.4	$2.35 \pm 0.61$	0.043	0.55	0.30	2
a1559	45	0.1058	$863 \pm 124$	14.06	11.5	0.33	2.3	$3.61 \pm 0.59$	0.193	0.21	0.02	0
a1564	57	0.0790	$633 \pm 57$	5.17	5.51	0.21	1.7	$1.62 \pm 0.40$	0.072	0.29	0.11	1
a1566	28	0.1015	$561 \pm 69$	3.52	4.04	0.24	1.5	$1.65 \pm 0.40$	0.019	0.67	0.24	1
a1577	16	0.1388	$359 \pm 123$	1.07	1.99	0.77	1.0	$1.99 \pm 0.34$	0.095	1.14	0.72	2
a1579	15	0.1033	$286 \pm 86$	1.00	1.15	0.73	1.0	$0.46 \pm 0.18$	0.033	0.50	0.23	1
a1581	16	0.1503	$521 \pm 92$	4.85	4.17	0.38	1.6	$3.97 \pm 0.61$	0.103	0.46	0.22	2
a1599	30	0.0855	$322 \pm 38$	0.84	0.58	0.40	0.9	$10.98 \pm 7.96$	3.660	0.09	0.15	0

Name	$N_{mem}$	$z_c$	$\sigma_c$	$M_{200}$	$M_{200,red}$	$er_M$	$r_{200}$	$L_{op}$	$L_X$	$er_{L_X}$	$P_{DS}$	X-class
a1620	67	0.0846	$782 \pm 53$	9.90	8.39	0.15	2.1	$4.76 \pm 0.94$	0.002	4.00	0.04	0
a1621	32	0.1037	$551 \pm 61$	2.12	2.24	0.31	1.2	$10.03 \pm 7.43$	0.088	0.46	0.03	0
a1646	27	0.1055	$573 \pm 88$	2.14	1.77	0.39	1.2	$2.57 \pm 0.86$	0.219	0.23	0.71	0
a1650	70	0.0839	$799 \pm 87$	11.14	9.51	0.22	2.1	$4.00 \pm 0.75$	3.134	0.06	0.36	0
a1659	15	0.1067	$383 \pm 79$	1.61	1.76	0.38	1.1	$1.02 \pm 0.21$	0.028	0.62	0.80	2
a1663	86	0.0830	$703 \pm 60$	7.62	7.57	0.17	1.9	$3.01 \pm 0.52$	0.548	0.15	0.22	0
a1674	17	0.1051	$549 \pm 98$	4.05	4.15	0.46	1.5	$2.24 \pm 0.41$	0.172	0.26	0.46	0
a1678	16	0.1689	$390 \pm 124$	1.98	1.64	0.67	1.2	$1.90 \pm 0.50$	0.143	0.50	0.14	1
a1692	54	0.0845	$561 \pm 65$	4.69	3.75	0.24	1.6	$2.00 \pm 0.42$	0.090	0.35	0.56	0
a1701	21	0.1239	$413 \pm 54$	1.15	1.0	0.49	1.0	$1.76 \pm 0.45$	0.138	0.86	0.49	1
a1750	115	0.0858	$784 \pm 41$	10.27	9.43	0.12	2.1	$12.05 \pm 2.00$	1.770	0.10	0.00	0
a1767	127	0.0705	$884 \pm 55$	11.57	8.68	0.14	2.2	$3.59 \pm 0.64$	1.329	0.05	0.17	0
a1773	82	0.0773	$779 \pm 74$	9.07	6.43	0.17	2.0	$4.57 \pm 0.66$	0.753	0.13	0.71	0
a1780	55	0.0776	$450 \pm 46$	2.51	2.72	0.22	1.3	$2.55 \pm 0.36$	0.033	0.61	0.17	1
a1809	99	0.0795	$716 \pm 52$	5.83	5.05	0.16	1.7	$5.30 \pm 1.13$	1.002	0.09	0.85	0
a1872	12	0.1480	$694 \pm 138$	3.89	–	0.43	1.5	$1.95 \pm 0.47$	0.253	0.30	0.05	0
a1882	55	0.1396	$733 \pm 99$	7.44	6.25	0.26	1.9	$13.29 \pm 1.42$	0.192	0.39	0.19	0
a1918	20	0.1402	$935 \pm 129$	16.26	12.3	0.30	2.4	$5.73 \pm 1.68$	2.448	0.08	0.60	0
a1937	13	0.1380	$223 \pm 50$	0.23	0.21	0.62	0.6	$1.02 \pm 0.29$	0.239	0.47	0.32	0
a1938	18	0.1376	$601 \pm 70$	4.95	5.78	0.26	1.6	$8.82 \pm 3.74$	0.714	0.22	0.52	0
a2026	51	0.0908	$753 \pm 59$	6.73	5.43	0.19	1.8	$4.44 \pm 1.20$	0.141	0.31	0.80	0
a2030	51	0.0915	$460 \pm 54$	2.27	1.80	0.25	1.3	$2.50 \pm 0.40$	0.081	0.35	0.79	0
a2050	34	0.1193	$826 \pm 165$	10.84	7.89	0.36	2.1	$4.85 \pm 0.87$	1.505	0.14	0.26	0
a2082	31	0.0862	$380 \pm 111$	1.84	1.42	0.56	1.2	$1.99 \pm 0.33$	0.065	0.38	0.56	0
a2094	36	0.1446	$606 \pm 110$	4.41	3.01	0.35	1.6	$5.18 \pm 0.65$	0.815	0.24	0.90	0
a2118	24	0.1416	$572 \pm 91$	4.41	3.34	0.32	1.6	$3.39 \pm 0.91$	0.158	0.37	0.32	1
a2149	60	0.0650	$330 \pm 46$	1.49	1.09	0.28	1.1	$2.13 \pm 0.33$	0.400	0.08	0.87	0
a2196	19	0.1340	$422 \pm 131$	2.17	2.71	0.58	1.2	$2.72 \pm 0.45$	0.492	0.17	0.80	0
a2211	15	0.1361	$493 \pm 100$	2.71	3.32	0.38	1.4	$0.81 \pm 0.32$	0.050	0.50	0.92	1
a2235	15	0.1492	$855 \pm 195$	12.24	12.2	0.47	2.2	$6.26 \pm 0.96$	1.176	0.14	0.91	0
a2243	36	0.1067	$759 \pm 85$	6.37	6.62	0.29	1.8	$2.13 \pm 0.38$	0.357	0.15	0.18	0
a2244	83	0.0993	$1062 \pm 61$	14.89	11.7	0.13	2.3	$6.84 \pm 0.71$	4.005	0.04	0.05	0
a2255	176	0.0801	$1121 \pm 67$	19.56	16.7	0.12	2.6	$11.14 \pm 2.83$	2.443	0.02	0.54	0
a2259	16	0.1600	$1080 \pm 15$	18.15	19.2	0.30	2.5	$11.32 \pm 1.78$	2.913	0.09	0.01	0
a2356	23	0.1195	$716 \pm 85$	5.84	5.45	0.25	1.7	$3.30 \pm 0.59$	0.670	0.18	0.31	0
a2379	14	0.1234	$531 \pm 105$	3.23	–	0.39	1.4	$3.29 \pm 1.24$	0.027	1.40	0.44	2
a2399	111	0.0579	$569 \pm 37$	4.09	3.19	0.14	1.5	$3.54 \pm 0.43$	0.490	0.12	0.07	0
a2428	42	0.0839	$420 \pm 23$	2.17	2.12	0.15	1.2	$2.57 \pm 0.67$	1.351	0.14	0.84	0
a2433	16	0.1195	$257 \pm 44$	0.50	0.33	0.40	0.8	$0.84 \pm 0.22$	0.092	0.47	0.66	0
a2448	38	0.0820	$447 \pm 62$	2.56	2.14	0.28	1.3	$2.05 \pm 0.49$	0.029	0.54	0.64	2
a2505	21	0.1100	$366 \pm 57$	0.94	1.01	0.40	1.0	$1.58 \pm 0.29$	0.238	0.28	0.00	0
a2561	13	0.1634	$405 \pm 91$	1.17	1.23	0.50	1.0	$2.16 \pm 0.38$	1.720	0.25	0.72	1
a2564	20	0.0828	$339 \pm 70$	1.25	1.40	0.45	1.0	$0.93 \pm 0.20$	0.041	0.38	0.45	0
a2593	167	0.0419	$570 \pm 55$	4.53	3.68	0.18	1.6	$3.24 \pm 0.53$	0.485	0.07	0.74	0
a2670	109	0.0761	$804 \pm 51$	9.40	9.32	0.13	2.0	$5.08 \pm 0.56$	1.255	0.10	0.73	0
a2705	33	0.1165	$452 \pm 64$	3.45	3.65	0.30	1.5	$3.77 \pm 0.58$	0.018	0.50	0.03	1